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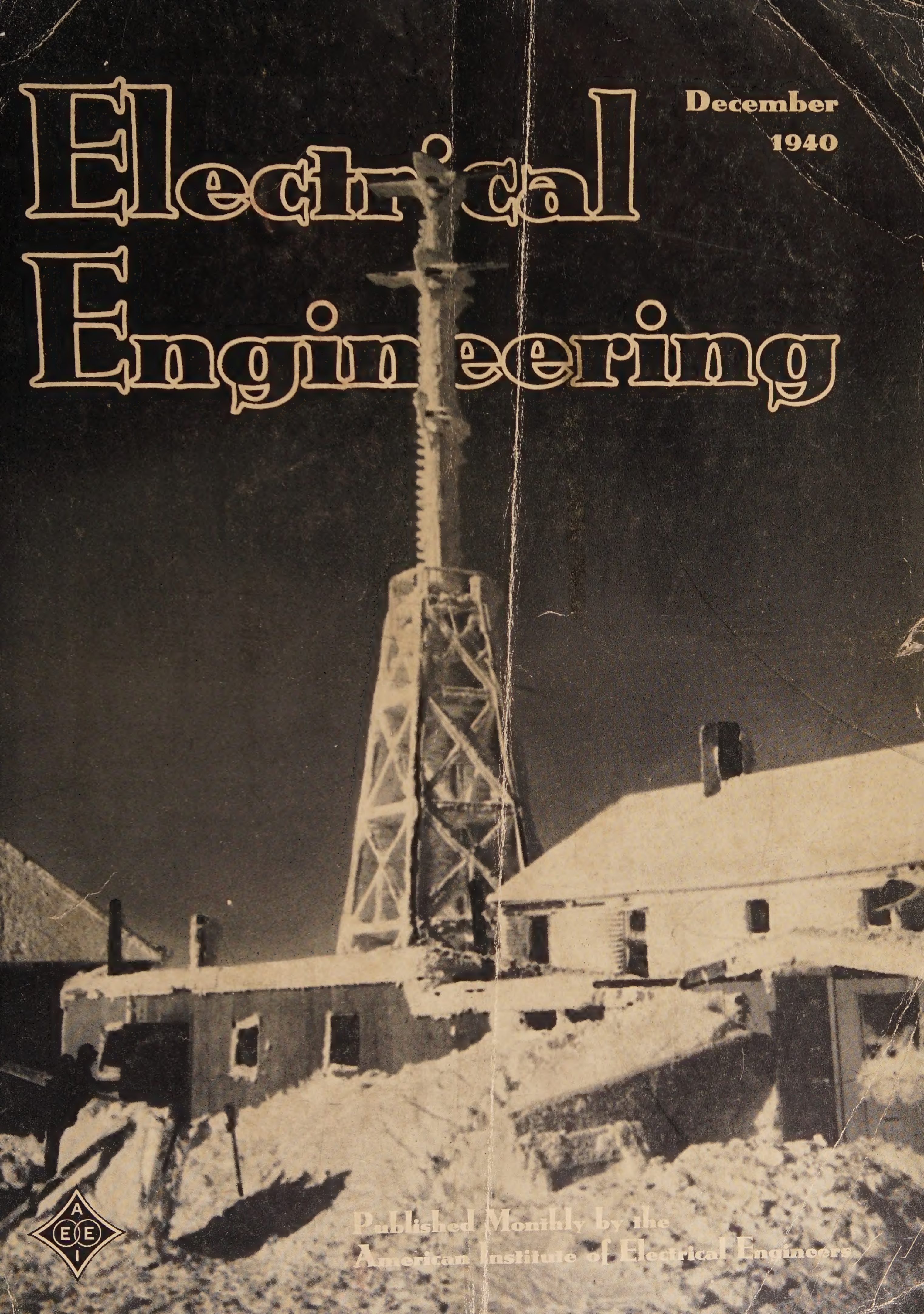
December
1940



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for December 1940—

The Cover: New frequency-modulation transmitter of the Yankee Network on the summit of Mount Washington, N. H.; an article on the evolution of frequency modulation appears on pages 485–93

Transactions Section *(Follows EE page 528; a preprint of pages 643–682 of the 1940 volume)*

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High Lights • •

"Blind" Landing. For some years radio aids to air navigation have made it possible for airplane pilots to fly when weather conditions are such that they cannot see the ground, but flights still must be cancelled when conditions at the destination are such that the pilots cannot see to land. Most promising of the various attempted solutions of this number 1 problem of aviation are ultrahigh-frequency radio systems, in which directive beams radiated from transmitters on the ground are received on the air planes and translated into appropriate instrument indications, thereby furnishing pilots with information that will enable them to land regardless of weather conditions. One such system has been developed to the point where it is being installed at ten important airports throughout the United States for an extended period of instrument or "blind" landing tests (*pages 495–502*).

Electronic Tubes. During the past decade the variety of types and the applications of electronic tubes increased greatly. A review of progress in the use of tubes in this period divides into two parts: the field of communication, and other uses. In communication, radio has advanced steadily to higher frequencies, broad-band carrier systems have been introduced in telephony, and television and frequency-modulation broadcasting have appeared—progress in which electronic devices have had an important role (*Transactions pages 643–9*). Nearly the whole period during which tubes have been applied in other than the field of communication is included in the past ten years. Here tubes are in competition with other devices, and must make their own way on the basis of lower cost (*Transactions pages 650–4*).

Frequency Modulation. Because of its great advantages over the present amplitude-modulation system of radio communication, the frequency-modulation system, under development for the past several years, now bids fair to become the dominant system in radiobroadcasting. In this issue, Major Edwin H. Armstrong, its inventor, traces the history of this new method of communication, outlines its advantages, indicates its present status, and predicts that "within the next five years the existing broadcast system will be largely superseded" (*pages 485–93*).

Impregnated-Paper Insulation. The requirement of mechanical flexibility in cable is at the root of the present method of applying paper insulation in spiral tape form in successive layers, but it is not always possible to retain maximum flexibility and maximum dielectric strength and stability. Paper selection should ensure the optimum combination for a particular cable; one factor is the thickness of the paper. Accelerated voltage-time tests have been made with this as the variable (*Transactions pages 660–3*).

National Defense. Among recent developments in national defense preparations of particular significance to the engineering profession are the announcement of a $9,000,000 program of Government-financed defense-personnel trainining in the engineering colleges (*pages 521–2*) and the National Resources Board's recent request for co-operation by engineering and other societies in preparing a roster of scientific and specialized personnel in the United States (*page 521*).

Nomography. Many computations in electrical-engineering work, particularly those involving the repeated substitutions of several variables in the same equation, can be expedited by the use of nomographic charts. In an article in this issue, the basic theory underlying these charts is outlined, and the application of the method illustrated by several examples involving familiar equations (*pages 505–08*).

Current Transformers. Most of the information concerning current transformers has been derived from tests on models. A new method of calculating the accuracy of current transformers, making use in so far as possible of the well-established power-transformer formulas, avoids the making and testing of models and enables the design to be made for a specific application (*Transactions pages 663–8*).

Reference Values. Engineering measurements frequently require that readings taken with the prevailing conditions of temperature, humidity, and barometric pressure be referred to standard reference values. At best all reference values must be a compromise for broader variations encountered by equipment in service, and therefore their number should be minimized (*Transactions pages 669–75*).

New Code. The 1940 National Electrical Code, recently approved as an American Standard, embodies significant changes as compared with the last previous edition (1937). In an especially prepared statement, the chairman of the committee responsible for compiling the Code discusses some of these changes (*pages 503–04*).

Potential Devices. Several limitations govern the rating and application of capacitance potential devices. To supply the need for co-ordinated practice, a paper outlining the basis of rating for the purpose of formulating standards has been prepared at the request of the AIEE relay subcommittee (*Transactions pages 676–80*).

Radio-Frequency Measurements. Although the same basic principles are used in measurements at power and radio frequencies, different techniques are required because of changes in circuit elements with frequency. The art is growing rapidly as new instruments become available (*Transactions pages 654–9*).

Detecting Ionization. A cathode-ray oscilloscope used in connection with an appropriate air-core reactor has been found to detect ionization in electrical apparatus at or below the minimum voltage at which radio interference may be noted by the "radio noise influence voltage" method (*Transactions pages 680–2*).

ECPD Annual Meeting. A complete list of engineering-school curricula accredited by the Engineers' Council for Professional Development as of October 24, 1940 appears in this issue (*pages 522–3*), in addition to a report of the annual meeting held that date (*pages 524–5*).

Winter Convention. Inspection trips are being emphasized by the 1941 winter convention committee in its plans for the convention at Philadelphia, Pa., January 27–31. Trips planned at present are outlined in this issue (*pages 510–12*).

Greetings From The President. A Christmas message to Institute members from President Royal W. Sorensen presents impressions gained in his presidential travels, and observations on Institute membership and on national defense (*pages 509–10*).

AIEE Budget. The report of Institute income and expenditures for the year ending September 30, 1940, and the budget for the year 1940–41, are presented in tabular form, accompanied by a report from the finance committee (*page 513*).

Coming Soon. Among special articles and technical papers currently in preparation for early publication are: an article on practical applications of research by E. S. Lee (F'30); an article discussing sun-spot disturbances of terrestrial magnetism by W. F. Davidson (F'26); a paper describing an investigation of the starting requirements of a 660-horsepower locomotive Diesel engine by J. C. Davidson (A'07) and R. Lamborn (A'26); a paper on the application of electricity for the auxiliaries of railroad trains by J. E. Gardner (M'37); a paper describing some characteristics and applications of negative-glow lamps by H. M. Ferree (A'40); a paper on vario-losser circuits by W. R. Bennett (A'40) and S. Doba; a paper on power-factor testing of transformer insulation by J. B. Hodtum (M'26); a paper describing an improved a-c pilot-wire relay by J. H. Neher (M'38) and A. J. McConnell (A'36); a paper on superposition methods for calculating effects of additions to power systems by V. G. Rettig (A'32); a paper on possibilities and methods of extending a carrier-current relay channel to other uses by R. M. Smith (A'35) and S. L. Goldsborough (A'24); and a paper describing a push-button-tuned 50-kw broadcast transmitter by R. J. Rockwell and H. Lepple.

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Evolution of Frequency Modulation

EDWIN H. ARMSTRONG

SOME 60 years ago the electric-power industry began the development of a system of distribution which all are now agreed was not the right system. I am referring of course to the low-voltage d-c system. The inevitableness of its replacement by the high-voltage a-c system is now obvious to everyone, although the literature of the transition stage reflects a period of violently conflicting opinion.

A part of the radio industry, in fact by far the largest part, is about to pass through a similar transition. It has become obvious that the present system of broadcasting is not the best, and that its faults are readily curable by the introduction of new technical methods. The characteristics of this new system are such as to provide practically perfect solutions of most of the troubles of the present structure.

Embracing the substance of lectures presented before many AIEE Sections and other groups, and particularly of an address delivered at the 1940 AIEE Pacific Coast convention, this article by the inventor indicates briefly how the frequency-modulation system of radio communication differs from the present amplitude-modulation system, traces the history of this new system, points out its advantages over the amplitude-modulation system, and indicates the extent of its probable applications in the future.

These faults are, specifically referring to the broadcast industry: the interruption or marring of the transmission by natural (lightning) or man-made static; the inability either to transmit the full musical range because of a lack of available channel space in the frequency spectrum, or to transmit that part which can be transmitted with full fidelity; the drastic mutual curtailment of the service ranges of two stations on the same wave lengths, even though separated hundreds of miles; and the distortion of the reproduction at certain points in the transmission paths by a phenomenon of propagation known as selective side-band fading. These difficulties and disabilities of present-day broadcasting are about to disappear with the introduction of a new system which has become popularly known as "frequency modulation," although much more is involved than a method of modulation per se.[1] Some 15 broadcast stations employing this system are now in operation and some hundreds are projected.

The problems solved are not merely technical ones. Since the system is primarily adapted for use in the ultra-high-frequency part of the spectrum, so much new frequency space becomes practically available that it has become possible to allot channel facilities to every town in the country. The factor that determines whether a community may have a station to serve its local needs is no longer the availability of channel space, but the economic ability of the community to support it. The development of local broadcast service within these smaller communities will play an increasingly important part in the broadcasting of the future.

MODULATION

Modulation in radio signaling is the process of changing some characteristic of the radio wave in accordance with the intelligence to be transmitted. The earliest form of modulation was the interruption or the breaking up of the radiated energy into the long and short pulses of the Morse code by means of a telegraph key, although in those days the term "modulation" was not used. Subsequently, with the introduction of continuous-wave generators, as distinguished from the "damped" wave or spark type of transmitter, it became possible to superimpose the characteristics of the voice or music on the radio wave. The method employed followed closely upon an early form of wire telephone transmission in which the strength of a current flowing through the line was varied in accordance with the tones of the voice, the number of times per second the direct current was "modulated" above and below its normal value corresponding to the frequency of the tone to be transmitted (considering, for example, a single tone), and the magnitude of the change corresponding to its loudness. In the earliest form of radio telephony the strength of the antenna current at the transmitter (in this case alternating several hundred thousand or more times per second) was varied in amplitude by a microphone connected in the path of the current. At the receiver, in the circuits of which currents corresponding in form to those transmitted were flowing, the variations in the amplitude of the high-frequency current were converted by means of a rectifying detector into currents corresponding in frequency and amplitude to those which the microphone would have created were it "modulating" a direct current. These currents may be observed in an ordinary telephone receiver.

The difficulties of handling large antenna currents by either a single microphone or a group of microphones led to various proposals for another form of modulation known then as "wave length" modulation. In this method, the amplitude of the antenna current remained unchanged, but the wave length or frequency was periodically increased above and decreased below a certain resting value,

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EDWIN H. ARMSTRONG is professor of electrical engineering, Columbia University, New York, N. Y. Major Armstrong ranks as one of the outstanding radio inventors of all time, having previously contributed the inventions of the regenerative circuit, the superheterodyne circuit, and the superregenerative circuit.

1. For numbered references see list at end of article.

the number of times per second the frequency was swung about the midpoint being determined by the frequency of the tone to be transmitted, and the extent of the change above and below (or the "deviation" from) the mid-frequency point being proportional to the strength or loudness of the tone. It was proposed to effect this kind of modulation at the transmitter by changing the inductance or capacitance of the circuit controlling the frequency of the oscillation generator by means of some electrostatic or electromagnetic microphone. Since no change in amplitude of the radio wave was produced, the transmission could not be received by the ordinary means. It was proposed to effect reception of waves with this type of modulation by causing the changes in frequency in the received wave to produce changes in amplitude by the use of mistuned selective circuits so that as the incoming variable-frequency current came closer into or receded farther from the resonant frequency of the selective circuit, the amplitude of the currents therein would be correspondingly varied and so could be detected by the usual rectifying means. No practical success attended these proposals, and the literature attests the fact that the early art struggled on with amplitude modulation. About 1914 the advent of the vacuum-tube modulator so completely solved the problems of amplitude modulation that for almost a decade frequency modulation was forgotten.

In 1922 the possibility of its use as a means of reducing the band width required to transmit a given range of frequencies was examined mathematically by Carson[2] who dispelled the illusion that a saving in spectrum space could be obtained over that required by the amplitude-modulation method. Carson proved that at least the same and usually a greater space was required by the frequency-modulation method. Other conclusions unfavorable to the frequency-modulation method were reached. The principal conclusions were subsequently confirmed by other mathematical treatments.

"STATIC"

The major problem of radio signaling for about 30 years has been the interference caused by various forms of natural and man-made electrical disturbances. While radio communication has always been subject to disturbances during lightning storms, the introduction of the vacuum-tube amplifier and the regenerative circuit in 1912 made the problem an ever-present one, as almost any signal could be received, however weak, provided it could be separated from the disturbing impulses which likewise, however weak, were always present. With the coming of broadcasting, which brought the location of the receiving system into areas where high levels of "man-made static" existed, and with the improvements in the sensitivity of the receivers themselves, which finally reached a point where fluctuations in the flow of electrons in the early stages of the amplifier circuits became capable of producing disturbances, the noise problem became the all-pervading one in the art.

Realization of the nature of the problem by those engaged in its study developed slowly. Following the introduction of the new methods of reception in 1912, a vast amount of work was done on the theory that the disturbing waves of natural origin were different in kind from those used in signaling and that circuit arrangements could be devised to differentiate between them. The patent literature of the art of this time furnishes an illuminating illustration of the amount of ingenuity that can be exercised along lines of unsound theory.

It was finally realized that the nature of these disturbances is that of a spectrum which contains all component frequencies, some of which always coincide with those being used in any particular case for transmitting the signal. Carson placed the matter on a quantitative basis in 1925.[3] Subsequently it was shown that many of the man-made disturbances are similar in make-up to those of natural origin and finally that the constitution of the disturbances originating in the irregularities of the motion of the electrons in tubes and circuits is likewise that of a spectrum. The amount of energy absorbed by any electrical system subjected to disturbances of this character depends on the width of the frequency band passed by the selective circuits of the system. Consequently it became a principle of design to make the admittance band of a receiver just sufficiently wide to pass the frequency components necessary to convey the signal, and no wider. The presence of the residual noise came to be accepted as a necessary evil.

Subsequent to the publication of the 1925 Carson article,[3] it occurred to the writer that the use of a system of signaling in which only changes in frequency of a transmitted wave could be observed in a receiver (which was made nonresponsive to amplitude changes) might furnish a means of distinguishing between the desired and undesired currents. An experimental investigation under actual working conditions using a receiver provided with a device for limiting out amplitude changes led to the conclusion that the currents set up in the receiving system by the waves of natural origin were modulated in frequency as well as in amplitude and that no major improvement could be thus effected. These observations were made with the frequency band width of the transmission and reception kept to the narrowest possible limits.

During the course of this work, however, an observation was made which seemed to indicate that the changes in frequency of the disturbing currents were limited in extent. This suggested the idea that if the transmitted wave were modulated widely in frequency and if the receiver were made nonresponsive to amplitude changes, feebly responsive to small changes in frequency, and fully responsive only to the wide frequency changes of the signal, a means of differentiating between desired and undesired currents might be found. With this relatively crude conception of a possible solution the necessary experimental work was undertaken. It resulted in the discovery of a new principle in noise reduction, the application of which furnishes an interesting conflict with the principle that had been the guide to the art for years. In accordance with this principle it was found that in a frequency-modulation system which is not responsive to amplitude changes within its working limits (noise not greater than one-half the signaling current), the wider the band used in trans-

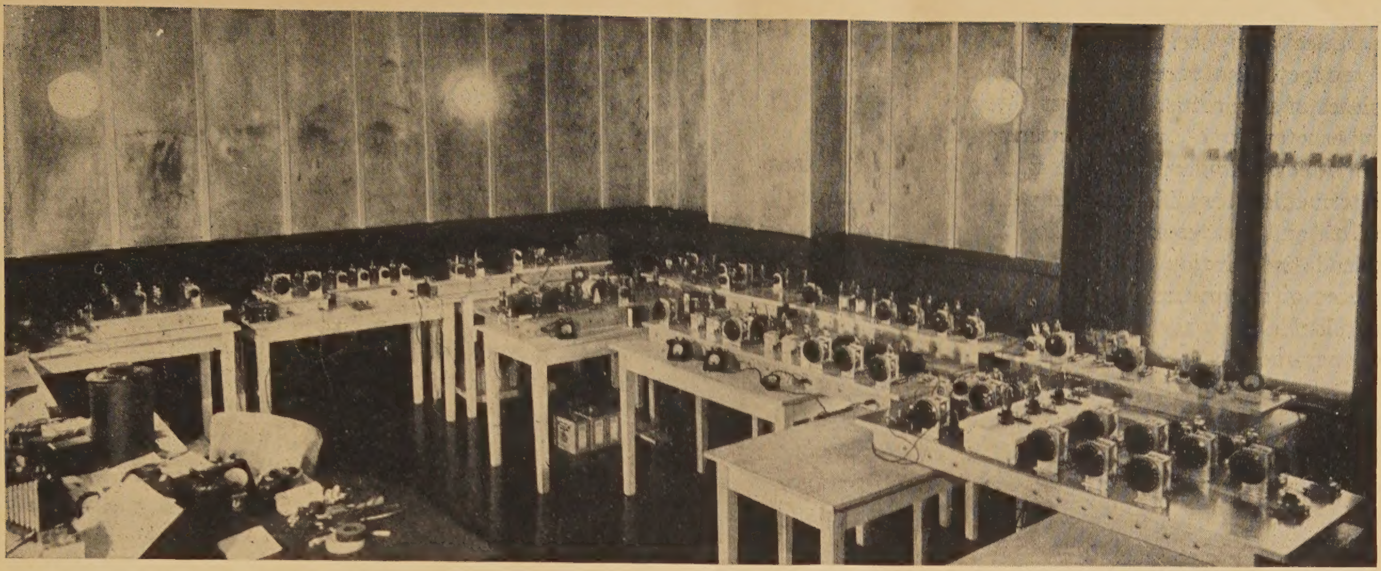


Figure 1. Frequency-modulator setup in shielded room used in early experimental work

mitting the signal the better the signal-to-noise ratio. The power gain of the signal-to-noise ratio increases as the square of the frequency band width used, and gains of a thousandfold or more can be realized in practice. Now the actual mechanism of the process by which the gain is achieved is much more involved than the foregoing explanation would indicate. It may be treated in various ways, but it is beyond the scope of this article to examine it in detail. A full explanation may be found in the writer's paper[1] presented before the Institute of Radio Engineers in 1935. The recent AIEE paper by Everitt likewise contains a detailed explanation.[4] Further reference to this process will be made hereinafter.

TRANSMITTING AND RECEIVING METHODS

In order to carry out the experimental investigation just mentioned, it was necessary to produce both transmitting and receiving equipment. An extensive experience with the known methods of obtaining frequency-modulated signals and their shortcomings led to the development of a new method which gave a complete solution to the problem of producing large frequency changes of a carrier at the relatively high frequencies where of necessity the new system had to operate in order to find available channel space. This method consists in employing the modulating current to shift the phase of a current derived from a source of fixed phase and frequency (usually about 200 kilocycles) by an amount directly proportional to the amplitude of the modulating current and inversely proportional to its frequency. The resulting phase shift is then multiplied several thousandfold by means of a series of frequency multipliers. By keeping the initial phase shift below 30 degrees substantial linearity can be obtained. Some three to five thousandfold multiplication is required in order to give an over-all frequency swing of 150,000 cycles at a transmitting frequency of 40 megacycles. Since it is desirable to perform the initial phase-shifting operation at a frequency of the order of 200,000 cycles the multiplication is carried out in two stages. The first stage usually converts its 200-kilocycle input to 12.8 megacycles; this frequency then is heterodyned with a frequency differing from 12.8 megacycles by a submultiple of the frequency which it is desired to transmit. Where the transmitter frequency is of the order of 40 megacycles the submultiple frequency may be of the order of 600 to 900 kilocycles. This current is then passed through a second series of multipliers until the desired output frequency is obtained, where its power is increased to any required amount by a series of amplifiers.

The receiving equipment follows amplitude-modulation

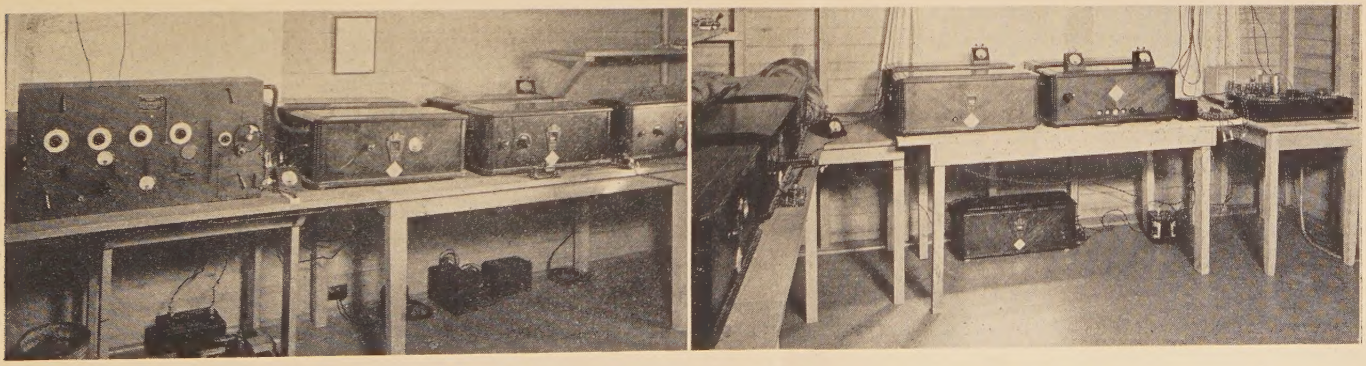


Figure 2. Early experimental frequency-modulation receiving equipment

practice along certain general lines. The superheterodyne method of reception is employed with two additional pieces of apparatus. The first detector or converter of the superheterodyne and the intermediate-frequency amplifier follow standard practice with the exception that the intermediate amplifier has a much broader frequency-band width and greater amplification than in the ordinary amplitude-modulation system. One of the two additional pieces of apparatus is a device for removing changes in amplitude from the received wave so that only pure frequency-modulated current is passed on for detection. This device is generally an overloaded vacuum-tube amplifier in which the screen and plate voltages are reduced to cause the tube to give a limited output; hence it is commonly referred to as a "limiter". It is connected to the output of the intermediate-frequency amplifier and usually requires several volts to be applied to its grid for effective operation. The second device is an arrangement of circuits in which the transmission characteristics with respect to frequency vary linearly over the range of the intermediate frequency through which the signal sweeps. It is placed after the limiter and before the detector, and its function is to convert the frequency changes linearly into amplitude changes. The name "discriminator" is commonly applied to this kind of device. Usually a differential or balanced type of detector is employed.

FIELD TESTS

The many years of research required to test out the principle were carried out in the Marcellus Hartley Research Laboratory at Columbia University, New York, N. Y. Since both ends of the system of necessity had to be under simultaneous observation, the transmitting and receiving equipment were located in adjoining rooms, the distance over which signals were transmitted being some 50 feet. During the winter of 1933–34 the system was demonstrated in the laboratory to the executives and engineers of the Radio Corporation of America for several months. Laboratory experiments in the "static eliminator" field being subject to quite justifiable suspicion, the transmitting equipment was removed from Columbia in the spring of 1934 and installed at the National Broadcasting Company's station located at the top of the Empire State Building in New York. This station had a 2-kw 44-megacycle transmitter which was originally intended for television, but which was not in use at the time. It was modified so as to transmit the wide-band frequency-modulation signals. Two modulators of the type heretofore described are shown in figure 1. They were located in a shielded room adjacent to the power-amplifier equipment and hence could be operated in the open as shown. The receiving system was located at Westhampton Beach, Long Island, about 70 miles from New York City. Figure 2 shows the receiving equipment as installed there in June 1934. The excellence of the results obtained in the initial tests surpassed all expectations, perfectly quiet reception being secured through the heaviest thunderstorms when all the standard broadcast services had been rendered utterly useless. As Westhampton Beach was obviously too favorable a site, the receiver was removed in July to Haddonfield, N. J., near Camden, a distance of about 85 miles from New York, where successful operation likewise was obtained.

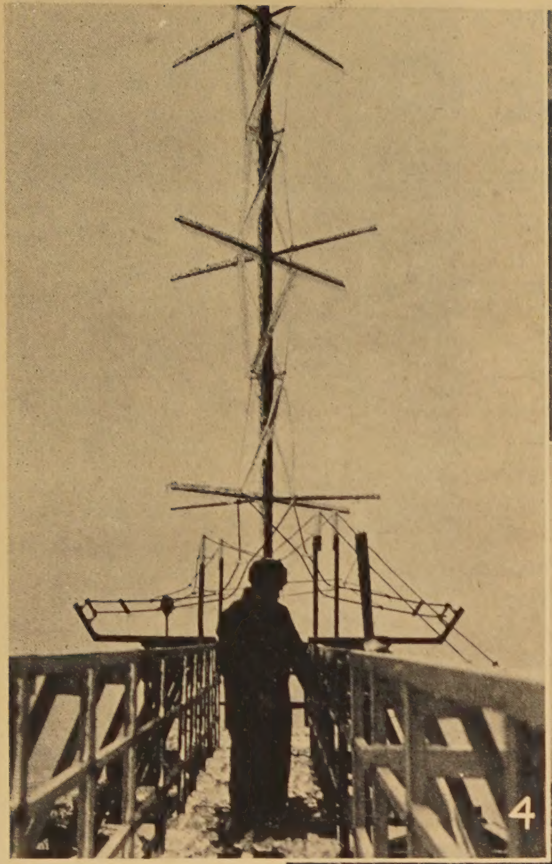
In all these tests much greater improvement in the signal-to-noise ratio was obtained than the thousandfold gain heretofore referred to, as in addition to the improvement due to the use of frequency modulation much less static is encountered on the ultrahigh frequencies than in the standard broadcast band. A pleasant surprise was the establishment of the fact that ultrahigh-frequency transmission, contrary to the accepted belief, did not stop abruptly at the horizon (about 45 miles for the Empire State tower) but could be successfully received up to at least three horizons. The complete absence of all the effects of selective side-band fading from which the standard band suffers was proved, and all the fears of limited coverage were set at rest.

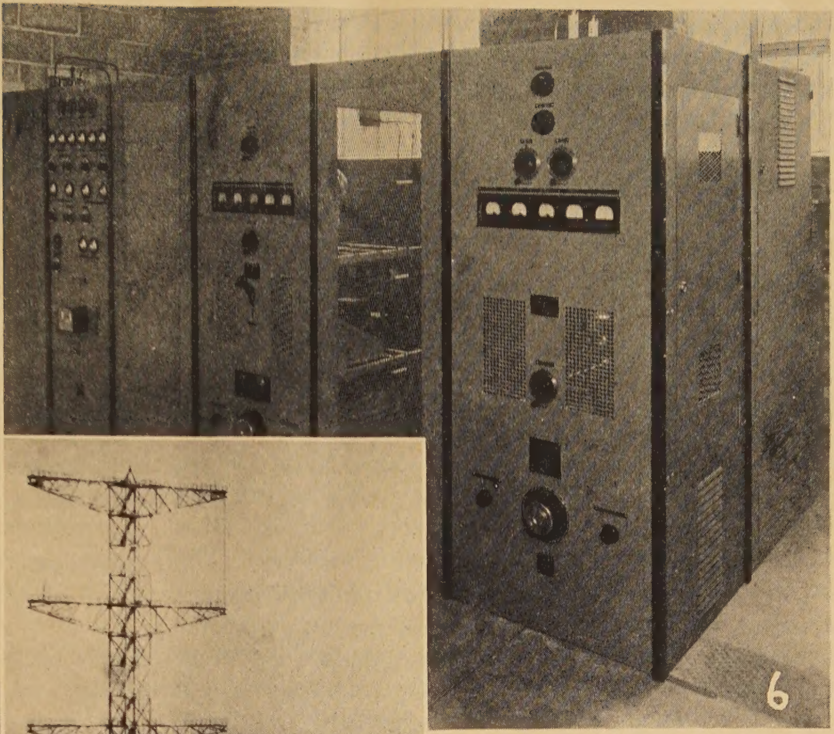
Up to this point the development of the system had proceeded in a normal way, similarly to the pattern followed in the introduction of many other inventions into American radio. However, numberless objections began to be raised regarding the utility of the new system; and although for over a year and a half tests were conducted under all conceivable conditions and repeated demonstrations and comparisons with the existing broadcast system carried out, the Radio Corporation declined to put the invention into public use. The Empire State transmitter was withdrawn from further frequency-modulation tests.

Work therefore was transferred to an amateur station W2AG located in Yonkers, N. Y. This station was equipped by its owner, C. R. Runyon, to operate on 110 megacycles and was used to demonstrate the system to the Institute of Radio Engineers in November 1935, on the occasion of the presentation of a paper[1] describing the system.

Next, application was made to the Federal Communications Commission for permission to construct a high-power 40-megacycle transmitter the success or failure of which would remove from the realm of academic discussion all questions concerning the efficacy of the system. The necessary authoritv was obtained at the end of 1936 and construction was started in the spring of 1937. The erection was completed and testing started in the fall of 1938. In the intervening time scores of demonstrations carried out from the Yonkers station, W2AG, were made to the representatives of the broadcast industry. As a result of these the Yankee Network decided to enter the field and proceeded with the construction of a station near Worcester, Mass. (Mt. Asnebumskit, Paxton). At about the same time, the management of Station WDRC at Hartford, Conn., entered the field with the erection of a station on Meriden Mountain, Meriden, Conn. Shortly thereafter the General Electric Company, as a result of the W2AG demonstrations, became interested and carried out and published the results of a long series of tests confirming the conclusions arrived at during the Empire State field tests.

The Alpine transmitter was ready for preliminary testing during the summer of 1938. All expectations were more than fulfilled and in the summer of 1939 the sta-





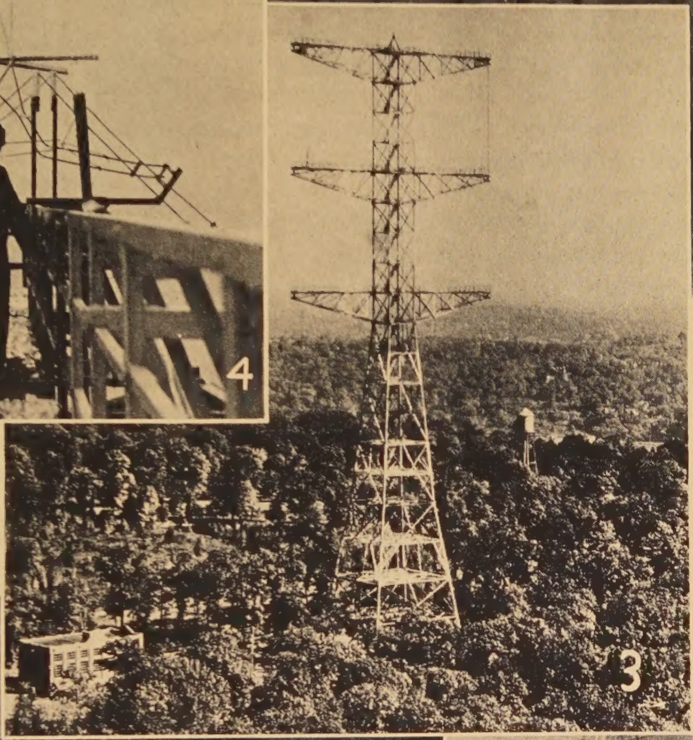
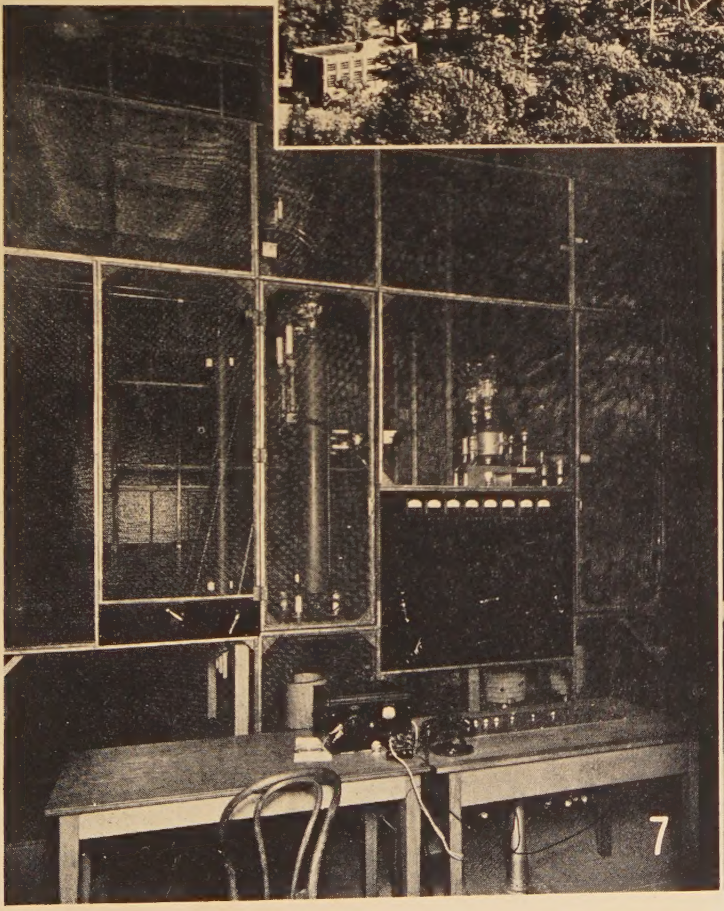
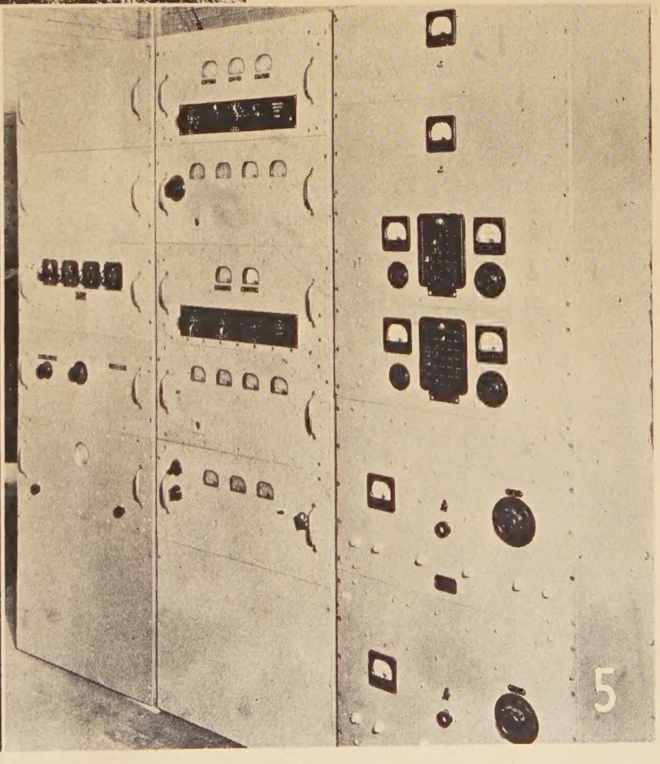


Figure 7. Last two power - amplifier stages

Figures 3–6. Frequency-modulation transmitter built at Alpine, N. J., by the author during 1937–38; note antenna between extremities of two upper arms (3); antenna structure, after a sleet storm (4); modulating equipment (5); frequency multipliers and low-power amplifiers (6)





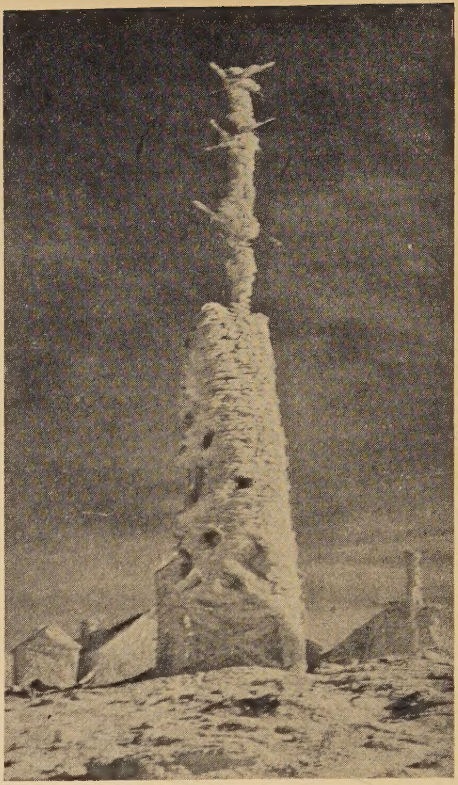
tion was placed on a regular operating schedule. A general idea of the transmitter as originally installed is given by figures 3 to 7. Since height above the surrounding terrain is of primary importance in ultrahigh-frequency transmission, the site selected was on the cliffs on the west side of the Hudson River known as the Palisades. A point about 500 feet above the river 17 miles north of New York in the village of Alpine was chosen. The antenna structure of the Alpine station is illustrated in figures 3 and 4. The height of the tower above grade is 400 feet. The length of the three cross arms is 150 feet and their vertical separation slightly over 80 feet. The radiating members of the antenna consist of a series of seven pairs of crossed rods about 11 feet long which are mounted on a boom supported between the tips of the two upper arms. These crossed rods or "turnstiles" are separated slightly less than half a wave length and are fed by a series of transmission lines which wind around the supporting member. The whole antenna is fed by an open-wire transmission line of about 500 ohms impedance which runs vertically through the center of the tower and horizontally over to the transmitter building for a total distance of about 700 feet. The efficiency of transmission appears to be of the order of 90 per cent.

The modulating equipment, similar in type to the "bread board" setup of figure 1, is shown in figure 5. The modulator is entirely contained in the center rack, the left-hand rack housing the ordinary line amplifiers, and the right-hand rack housing the power-supply equipment for operating the modulator and other units. Figure 6 shows a further series of frequency multipliers and low-power amplifiers for raising the power to a level of 1 kw at 40 megacycles. The last two power stages employ water-cooled tubes which raise the power respectively to 3 kw and to 40 kw. Figure 7 shows these amplifiers as installed in a shielded cage, which is necessary for the protection of the operating staff from the high field strength. The modulating and low-power units shown in these illustrations were built by the Radio Engineering Laboratories and the two high-power amplifier units by the RCA Manufacturing Company.

In the summer of 1939 the Paxton (figure 8) and Meriden transmitters were completed; and when they and the Alpine transmitter were placed on a regular operating schedule so that their performance could be observed daily, the broadcasting industry became convinced that a change was imminent. A dozen more stations were constructed and applications for over 150 more were on file with the Federal Communications Commission by the fall of 1939, when it was alleged that improper standards were being employed and that a band width narrower than 200 kilocyles could be employed more effectively. The granting of further construction permits was suspended pending an investigation by the Commission of this question and the question of providing additional channel space to accommodate the large number of applications for licenses. A public hearing by the Commission in March 1940, resulted in the approval of the 200-kilocycle band, the rearrangement of the allocation plan to increase substantially the assignment of channel space (42–50 megacycles) and the decision to grant commercial licenses. The Communications Commission has now resumed the issuance of licenses, and some 15 permits for commercial instead of merely experimental operation, have now been granted.

Figure 8. Interior of Paxton, Mass., transmitter building

Figure 9. Winter condition of experimental frequency-modulation antenna atop Mount Washington, N. H.



RELAYING

At the present time the wire-line facilities available for linking radio stations into networks are limited to the transmission of a frequency range up to about 5,000 or 6,000 cycles and have a residual noise level considerably greater than that required for the full dynamic range of even ordinary studio orchestral productions. Approximately the same limitation is imposed on the present-day radio stations by the lack of available frequency space and by the noise problem which results when receiver circuits and speaker systems are adapted to reproduce the full audio range of 15,000 cycles. These limitations are not imposed on the frequency-modulation system since the band width used is much in excess of the range of frequencies to be transmitted and the low noise level permits

the effective reproduction of the weakest overtones. Residual noise in the transmitting equipment is now better than −70 decibels, so that the signal-to-noise ratio over a large part of the service range of a high-power station can be held below this level. Since the bottleneck, at the present time and perhaps for a long time to come, lies in the wire connecting links, various radio relaying projects have been started.

The first of these was initiated by the Yankee Network to transmit the programs originating in its Boston studios to the top of Mt. Asnebumskit. The air-line distance is approximately 45 miles. Preliminary estimates of the cost of construction of the type of wire line required were in the neighborhood of $70,000, with doubtful guarantees of the noise level. The problem was solved by the use of a frequency-modulated 250-watt 130-megacycle transmitter located on the roof of the six-story studio building, arranged with a directional antenna to beam the transmission toward Paxton. At the receiving end a directional array likewise adds to the efficiency of the circuit.

The initial cost of the installation was a fraction of the estimated cost of the line, its maintenance cost is negligible, and its performance far better than could be obtained with any line facilities that could be furnished, even at the cost mentioned. The circuit has been in operation for over a year and has functioned perfectly through even the heaviest thunderstorms. Experience with this circuit has indicated ways of cutting the cost markedly. A second relay project which the Yankee Network is carrying out is the construction of relay stations to rebroadcast the Paxton transmissions. The first of these to be erected is located at the summit of Mt. Washington in northern New Hampshire, about 130 miles from Paxton. For over six months of the year the climate at the summit of this mountain is one of the severest in the world, winds of over 200 miles an hour with extremely low temperatures being frequently encountered together with a type of ice formation that imposes great mechanical stresses on the antenna structures. Two years ago a 100-foot tower was erected and a small transmitter installed to determine the practicability of the operation of ultrahigh-frequency transmission from an antenna the normal winter condition of which is shown in figure 9. Two winters' experience has resulted in a solution of the problems involved and a one-kilowatt frequency-modulation transmitter is now installed on the mountain (to be increased to ten kilowatts in the spring); regular operation will begin about November 15. The performance of this station will be watched with much interest throughout the radio world. A similar station located on a mountain in northern Vermont will complete the coverage of the northern half of New England. Several similar networks are projected in the southern Atlantic and the Pacific Coast states.

Another relaying circuit is now in daily operation between Alpine, N. J., and Meriden Mountain, Conn., and Alpine and Helderburg Mountain, N. Y., the station of the General Electric Company near Albany. The distances involved are about 70 and 130 miles, respectively. At the Helderburg station reception is effected in the ordinary way, and the recovered audio signaling current at a remotely located receiver is sent over a telephone line to the transmitter where remodulation occurs in the ordinary manner. At the Meriden station the 42.8 megacycles of the Alpine transmission is converted to the Meriden frequency of 43.4 megacycles and amplified up to excite the final power amplifier without the necessity of creating any audio-frequency current in the process. It has been found possible to do this with the receiving antenna located within 100 feet of the transmitting antenna, and the elimination of the processes of detection and remodulation has resulted in the removal of the distortion incident to these operations.

The future undoubtedly will see the introduction of chains of relaying stations equipped with highly directional antenna arrays operating on frequencies considerably higher than those used in broadcasting.

TRANSMITTING AND RECEIVING EQUIPMENT

Great improvement and simplification has been effected in the design of both transmitting and receiving equipment since the building of the initial transmitter at Alpine. It has been found possible to eliminate the intermediate water-cooled power stage and to drive the final 50-kw amplifier directly by a 2-kw air-cooled amplifier stage, this in turn being driven by a pair of 250-watt high-amplification beam tubes, all operating on 40 megacycles. The beam tubes are readily driven by a pair of triplers operating with a power output of 10 to 20 watts. Perfectly stable and reliable operation is obtained with this arrangement of the exciter stages. Figure 10 shows a complete modulating and exciter unit (2 kw). Figure 11 shows the 50-kw amplifier unit for the Paxton station during construction. These units together with the power-supply racks for the high-power amplifier are all that is required for the production of 50 kw of frequency-modulated power.

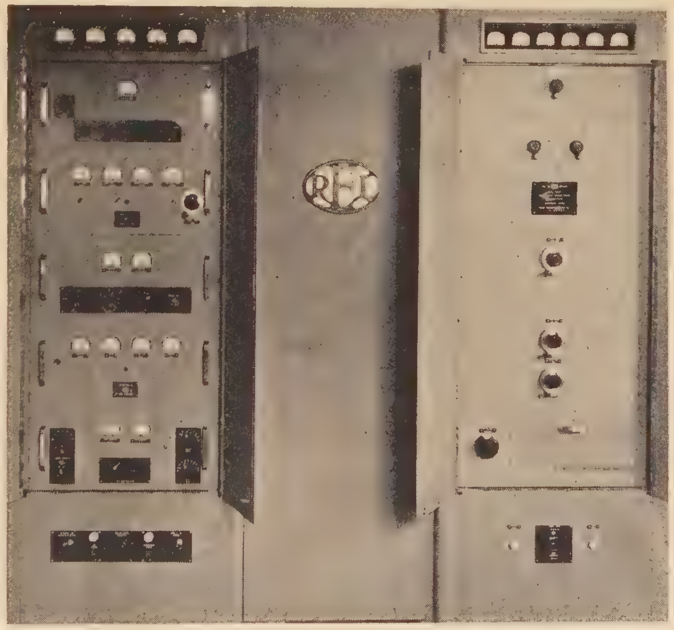


Figure 10. Modulating and power amplifier units of complete two-kilowatt transmitter

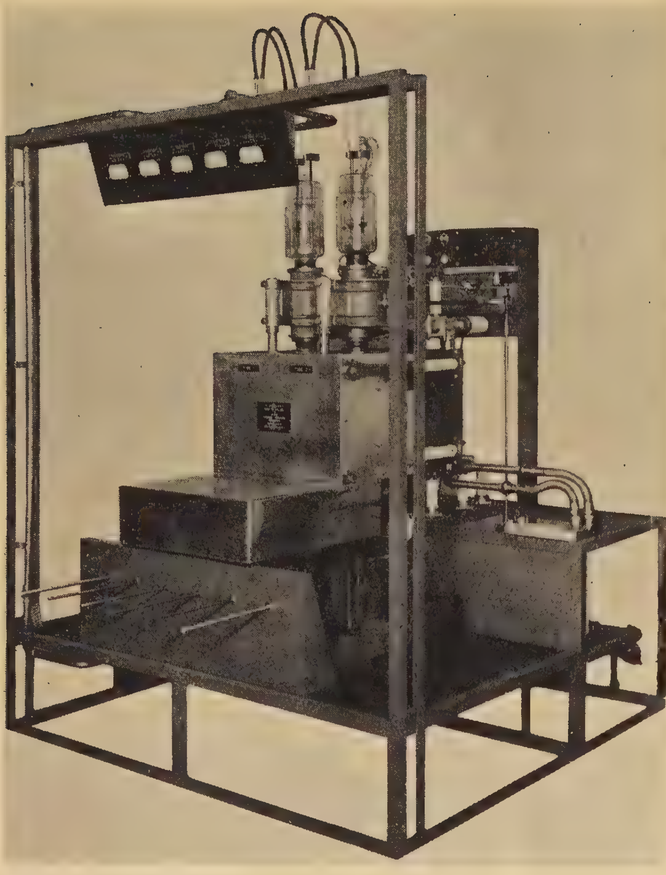


Figure 11. Power-amplifier unit of 50-kw frequency-modulation transmitter before mounting in shielded room

Similar progress has been made in receiver design, figure 12 showing a general-purpose receiver which operates effectively on a field strength of about ten microvolts per meter and gives an undistorted audio output of about 15 watts (a few watts only is necessary for home reception). Ten tubes are used, but with the production of double-purpose tubes specially designed to meet the requirements of this type of receiver further reduction in the number of tubes and parts is possible.

At the present time intensive commercial development of both transmitting and receiving equipment is under way, the General Electric Company and the Western Electric Company being now in position to supply transmitters and some dozen receiver manufacturers having on the market sets adapted to receive both the frequency-modulation and standard-broadcast amplitude-modulation transmissions.

SOME UNIQUE CHARACTERISTICS

There are some characteristics that are unique in the frequency-modulation system which have no counterpart in amplitude modulation. It is, of course, well known that when the carriers of two amplitude-modulated transmitters are sufficiently close in frequency to produce an audible beat, the service range of each of them is limited to that distance at which the field strength of the distant station becomes approximately equal to one per cent of the field strength of the local station. As a consequence, the service area of each station is greatly restricted; in fact, the service area of the two stations combined is but a small percentage of the area rendered useless for that frequency by the presence thereon of the two interfering stations.

With the wide-band frequency-modulation system, however, comparable interference between two transmissions does not appear until the field strength of the interfering station rises to a level of between 25 and 50 per cent of the field strength of the local one. The reason for this lies in the fact that while the interfering signal, in beating with the current of the local station under such conditions, may be producing a large change in the amplitude of the voltage applied to the current limiter, the system is substantially immune to such variations in amplitude. The only way in which the interfering signal can make its presence manifest is by superimposing some modulation of frequency on the frequency variations of the local signal. Under the conditions this "cross modulation" or phase shift superimposed upon the signaling current is limited to something of the order of a 30-degree change in phase, and the characteristics of the wide-band receiver are such that at least within the range of best audibility a phase shift of thousands of degrees in the signaling current is necessary to produce full modulation. Hence the 30-degree interfering phase shift superimposed upon the signaling current will produce little change in the rectified or detected current. As a consequence, the interference area in territory served by two frequency-modulation stations on the same channel is greatly reduced, as compared with amplitude modulation, and becomes, in fact, less than the area usefully served.

This property of the system, coupled with the fact that the propagation limits of ultrahigh frequencies are more sharply defined than those of the present broadcast frequencies, makes it possible to operate stations occupying the same channel space with much less geographical separation. Where desirable, it will be found practical to operate stations from 25 to 50 miles apart.

Figure 12. General-purpose frequency-modulation receiver having an undistorted audio output of about 15 watts

There is likewise a fundamental difference in the factors that govern distortion in the amplitude- and frequency-modulation equipment. Provided the circuit constants are properly designed for the frequency of the signaling currents, distortion in an amplitude-modulated transmitter or receiver depends principally on the linearity of the characteristics of the vacuum tubes employed. In frequency modulation, distortion is practically independent of the linearity of all the tubes that handle radio-frequency current and is dependent only on the phase shift introduced by the circuit components. These can be more readily designed and maintained to keep distortion below a desired limit. As a consequence, not only can aural effects be transmitted and reproduced with great fidelity, but the system is well adapted for multiplexing. It has been found possible to transmit simultaneously both an aural and facsimile program without interference between the two, the facsimile transmission being carried out on a channel of superaudible frequency. This was accomplished as early as 1934 over a distance of 85 miles in the original tests using the two-kilowatt transmitter at the Empire State Building in New York.

Figure 14. Connecticut State Police system: two-way 250-watt station at Wilton, Conn.

APPLICATION TO SERVICES OTHER THAN BROADCASTING

The system has important applications to various types of emergency communication services. Since the transmission of intelligible speech requires a much smaller range of frequencies than the full musical range—in fact a range of perhaps only 250 to 3,500 cycles—a smaller deviation of the transmitted frequency may be employed. It has been found practicable to make use of a total band width of 40 kilocycles in police service, and several installations are now operating effectively.

The largest project at the present time is that undertaken by the Connecticut State Police, who have in operation nine fixed stations and approximately 200 mobile stations equipped for two-way operation. The fixed stations are located on hill tops and have 250 watts power output. The car transmitters have approximately 25 watts power output. Thirty-mile communication between the cars and the fixed stations and five- to ten-mile communication between cars is easily obtained. This system was designed by Professor Daniel E. Noble (A'32) of the University of Connecticut. (See figures 13 and 14.)

The next largest project to be undertaken is in the city of Chicago, where some 200 mobile 25-watt car units are being installed. Numerous other projects for police services and for emergency-service use by power companies are being made, and it is doubtful if many new installations employing amplitude modulation will be made in the future. It is, of course, needless to say that there are many important military uses. In fact, in practically all ultrahigh-frequency applications where weight or portability is not too great a factor, the frequency-modulation system has found increasing use. The one important field where progress has been inexplicably slow has been television, where its advantages, particularly on the sound channel, could be effectively utilized. A limited use has been made in the relaying of the television sight channel.

Figure 13. Transmitter (left) and receiver in rear interior of car, Connecticut State Police system

CONCLUSION

Five years ago the writer said[1] that "the conclusion is inescapable that it is technically possible to furnish a broadcast service over the primary areas of stations of the present-day broadcast system which is very greatly superior to that now rendered by these stations." With the cost of transmitting equipment for the new system already below the cost of the equipment of the standard broadcast type (for the same power output) and with the cost of broadcast receivers approaching levels that will permit large-scale production and distribution, the conclusion is likewise inescapable that within the next five years the existing broadcast system will be largely superseded.

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Traffic Safety Lighting on the Pennsylvania Turnpike

FOUR types of illuminants—high-intensity mercury-vapor, sodium-vapor, fluorescent, and incandescent—are used for various types of lighting applications on the new Pennsylvania Turnpike which recently was opened to traffic. First important "super highway" in America, the new turnpike stretches 162 miles between Pittsburgh and Harrisburg, Pa., burrowing through the highest ridges of the Allegheny Mountains with seven mile-long tunnels. More than 110 miles of the four-lane road is straight, the maximum grade is three per cent, and the worst curve is six degrees.

Mercury-vapor lamps are used in lighting the seven tunnels, said to be the first tunnels ever lighted by this type of lamp; sodium-vapor lamps are used at the tunnel approaches and at traffic interchanges; fluorescent lamps are used inside the ticket offices, and incandescent lamps under the marquees over the driveway spaces at ticket offices. The lighting equipment was supplied by the Westinghouse Electric and Manufacturing Company.

Employing 1,060 250-watt high-intensity mercury-vapor lamps in open reflectors recessed into tunnel ceilings, the tunnel-lighting system is said to provide three times as much light output as could be obtained from incandescent sources of the same wattage. The lamps are mounted horizontally with their long axes parallel to the roadway. Intensities at the tunnel ends are of the order of 150 foot-candles, tapering down to $5^1/_2$ foot-candles at some 250 feet from the entrances. Such gradation eases the reaction of the motorists' eyes in going from daylight to the much lower illumination level in the tunnels. The tunnel lighting is designed for a driving visibility of well over 1,000 feet.

Emergency lighting systems operating from batteries also are provided for the tunnels. Emergency fixtures are spaced 300 feet apart in alternate rows, and furnish sufficient illumination for discernment of normal hazards. The seven tunnels are served by 242 emergency units. Batteries and controls are housed in control rooms at the tunnel portals. If the main power supply to any tunnel is interrupted, the emergency system automatically is placed in operation. The batteries are charged by gasoline-engine-driven generators, so that the length of time that the emergency lighting systems can function is limited only by the gasoline supply.

The tunnel-approach lighting extends an average of 1,800 feet out from the tunnel portals and employs 10,000-lumen sodium-vapor units. These lamps not only provide a good seeing light, but also act as caution signals. Luminaires are spaced at gradually increasing intervals, from 125 to 350 feet, progressing away from the tunnel portals. This lessens the contrast between the bright tunnel lighting and the comparatively dim illumination of automobile headlights when leaving a tunnel, and accomplishes the reverse effect when approaching a tunnel.

At traffic interchanges, sodium-vapor units are used not to supply high intensities, as at the tunnel entrances, but for cautioning approaching motorists. For this purpose 151 sodium-vapor units are used, an average of 14 per interchange, being placed at strategic points where caution signals are desirable—on turnouts, curves, and underpasses.

Entrance to one of the Pennsylvania Turnpike tunnels

In each ticket office, four 40-watt white fluorescent lamps provide an intensity of 45 foot-candles on the ticket-sellers' desks. Outside areas under the marquees which cover the driveway spaces are illuminated by incandescent units flush-mounted in the marquee ceilings. Six luminaires are used at every drive entrance, five of which are 200-watt units.

Each mercury-vapor lamp in the tunnels operates from an individual transformer, supplied from a 2,300-volt 60-cycle multiple circuit. The sodium-vapor lamps are connected in series on constant-current circuits through 6.6-ampere regulators. Other lighting units are fed from parallel circuits through distribution transformers. Total lighting load is 375 kw, and is supplied by four companies along the route.

Instrument Landing of Aircraft

Development of equipment for instrument landing of aircraft, popularly known as "blind" landing, has progressed to the point where ultrahigh-frequency radio landing equipment is to be installed at ten important air terminals throughout the United States by the Civil Aeronautics Administration. An extended period of service testing and pilot training will follow, and still further development is expected before such equipment is ready for use in regularly scheduled commercial flights. Experiments also have been made with a so-called micro-wave system using yet higher frequencies. The features of both systems are outlined briefly in this article, and three types of indicating instruments are described.

NOT many years ago, unfavorable weather conditions meant the cancellation of all aircraft flights. Subsequent development of radio aids to air navigation have made it possible for an airplane to *fly* with safety under conditions of poor visibility, but it still is necessary to cancel flights where conditions at the airport of destination are such that the pilot cannot see to land. The problem of *landing* an airplane under adverse weather conditions remains the most important problem in commercial flying today. The United States Civil Aeronautics Authority (now Civil Aeronautics Administration), realizing this to be the bottleneck of safe flying under conditions of low ceiling and poor visibility, has endeavored to overcome the difficulty by fostering the development of a suitable instrument landing system.

For more than ten years, experiments have been under way with various types of systems, but the most promising ones today are those utilizing ultrahigh-frequency radio waves. An experimental system of this type embodying the latest advances in the art was installed during 1938–39 at the Indianapolis, Ind., airport under auspices of the Civil Aeronautics Authority.[1] The performance of this equipment was so satisfactory that the Authority decided, early in 1940, to proceed with the installation of similar equipment at ten important airports throughout the United States. An extended period of service testing will follow.

Another system, similar to the Indianapolis system but utilizing higher frequencies and known as the micro-wave system, has been developed at Massachusetts Institute of Technology.[2]

Instrument-landing systems have been developed also by the National Bureau of Standards, the United States Army, Air-Track Manufacturing Corporation, Bendix Aviation Corporation, and other organizations. Only the so-called Indianapolis and micro-wave systems are discussed here, however, a description of all the systems obviously being outside the scope of this article.

ESSENTIALS OF ULTRAHIGH-FREQUENCY SYSTEMS

To make an instrument or "blind" landing, an airplane pilot must be provided with lateral guidance, vertical guidance, and position "fixes." Lateral guidance is necessary to enable the plane to land in the middle of the runway. Vertical guidance and position "fixes" combine to guide the plane to a landing point on the runway at the proper rate of descent, and to prevent overshooting or undershooting the runway. In the systems described in this article, four separate radio transmitters are required to provide this information: one for lateral guidance which produces the so-called localizer beam; one for vertical guidance which establishes the so-called glide path; and two for position fixes which provide vertical "marker beacons", one at the airport boundary and one about two miles from the boundary on the approach side. Special antenna arrays have been devised to produce beams having the desired characteristics. A complete set of four transmitters is required for each landing direction, except where the equipment is portable and can be shifted from runway to runway.

On the airplane, three separate radio receivers are used, one to receive the localizer beam, one the glide-path beam, and one the marker-beacon signals. Signals from all three transmitters are translated into appropriate impulses and applied to suitable instruments which provide the pilot with the necessary landing information. The procedure in making a typical instrument landing is outlined in figure 1.

Principal features of the Indianapolis and micro-wave systems are outlined briefly in succeeding portions of this article. Instruments developed for use with these systems also are described, as well as an instrument known as the "Flightray" developed by the Sperry Gyroscope Company.[3]

EQUIPMENT ON GROUND—INDIANAPOLIS SYSTEM

Four complete groups of transmitters have been installed at the Indianapolis airport, permitting instrument landings in any one of four directions (figure 2). All transmitters are connected to a monitor and control desk in the airport control tower by telephone lines so that the four transmitters for any of the landing directions can be turned on as required to meet local wind conditions. Calibrated instruments and signal lamps give qualitative and quantitative indications from the various transmitters. If the output of any transmitter should fall below a predetermined level, visual and aural alarms will indicate the trouble. Alarms also will operate if the runway localizer course should shift sufficiently to cause an airplane following the course to land off the runway. The Indianapolis

Much of the text and most of the illustrations in this article were drawn from two AIEE papers listed as references 1 and 2 at the end of this article and the Institute of the Aeronautical Sciences paper listed as reference 3. Special acknowledgment is made to P. D. McKeel, acting chief, radio development section, technical development division, Civil Aeronautics Administration, who supplied the diagram forming the basis of figure 1, together with the associated explanation.

1. For all numbered references see list at end of article.

equipment was developed and installed by the International Telephone Development Company.

Localizer Installation. Equipment for producing the localizer beam consists of a transmitter, antennas, modulator, and associated equipment, all housed in a wooden building approximately 12 feet square located off one end of the runway.

The localizer transmitter has an output of 300 watts, unmodulated, at a frequency of 109.9 megacycles. It has a crystal-controlled oscillator followed by three frequency-

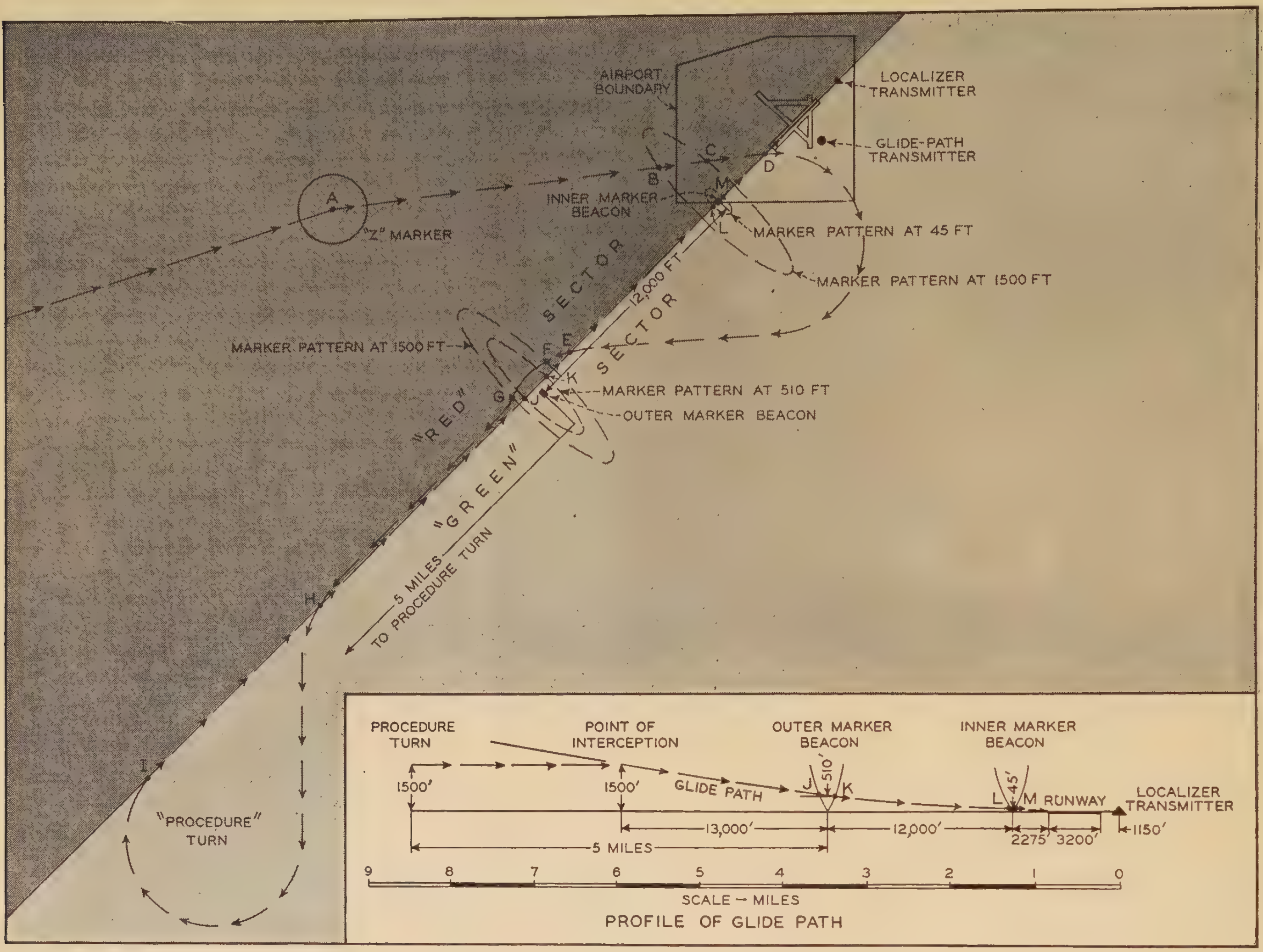


Figure 1. Diagrams showing how a typical instrument landing is made

The manner in which an instrument landing system operates can be illustrated by outlining the various steps required in making a typical landing. Suppose an airplane is approaching the airport at an altitude of 1,500 feet above the field from the left. Before beginning the descent, the pilot must maneuver his plane into proper position to intercept the glide path at the proper point and in the proper direction; then, by means of the information furnished by instruments on the airplane (see figure 13), this invisible pathway, produced by the electromagnetic fields radiated from the localizer and glide-path transmitters at the airport, guides the pilot to a safe landing on the airport runway.

After passing through the cone of silence or marker beacon at *A*, the pilot follows a course directly toward the airport. As the ship intercepts the field of the inner marker beacon at *B*, the pilot will observe audible and visual signals which continue to *C*. As the pilot proceeds along this course, the landing instrument will indicate that his ship is definitely in the "red" area of the localizer field. A definite and known time is required to fly this distance. Almost immediately after the inner marker beacon is passed, the instrument will indicate that the localizer course has been crossed (*D*). At this point, a "procedure" turn to the right is made, continuing until the plane again crosses the localizer course at *E*. The pilot then swings the ship into the localizer course and soon intercepts the field of the outer marker beacon at *F*; as with the inner marker beacon, visual and audible signals indicate when the ship has reached this point and continue to *G*. Tones of different pitch and visual signals of different color are used for the two marker beacons. From *G*, the pilot follows the localizer course for a distance of five miles, or to *H*, where the ship is swung left; a short flight in this direction is followed by a second "procedure" turn to the right, after which the localizer beam again is intercepted, at *I*. The plane now is in proper position to begin the descent (see profile diagram).

By keeping the plane on the course established by the localizer and glide-path beams, the pilot is able to bring the plane smoothly and safely to the airport runway. The beams radiated from the localizer and glide-path transmitters are received by the respective receivers on the airplane and are translated into visual indications that allow the pilot to follow the glide path with high accuracy. On the descent, the outer marker beacon signals again will be observed, between *J* and *K*; the altitude of the plane here should be about 500 feet, and the duration of the signals approximately 8 seconds. At *L*, the inner marker beacon signals will be observed; here, if the plane is descending properly, the altitude should be 45 feet and the signals will continue for $1^1/_2$ seconds (to *M*). Contact with the airport runway is made within a short interval after passing the inner marker beacon.

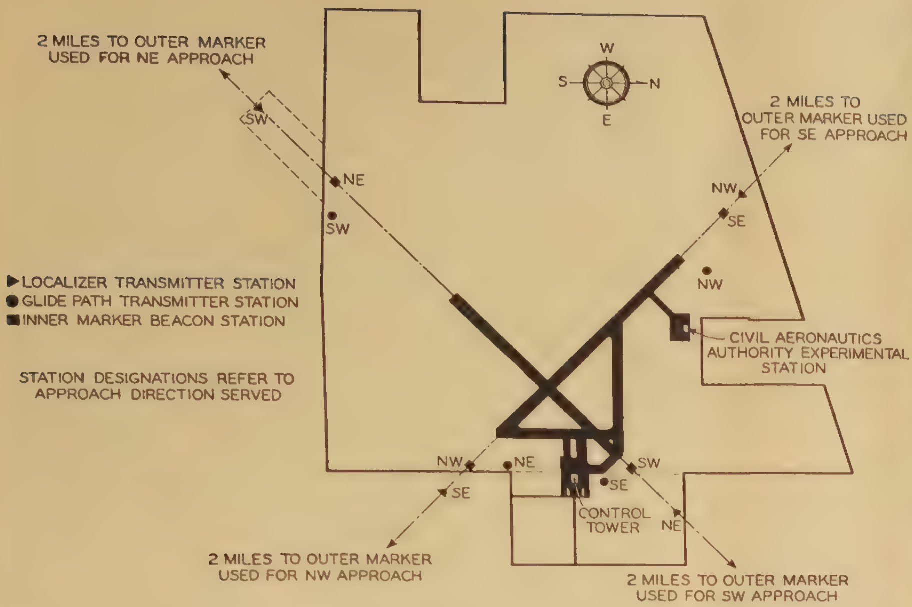


Figure 2. Plan view of Indianapolis, Ind., airport showing location of runways and instrument landing equipment

Figure 3 (right). Array of ultrahigh-frequency loop antennas used for the localizer beam at Indianapolis

multiplier stages to produce the output operating frequency. The last two stages are push-pull amplifiers operating at output frequency. A regulator holds the supply voltage constant within plus or minus one per cent for all normal variations of line voltage. Special precautions are taken to insure reliable operation during cold weather.

As few objects ordinarily found at an airport reflect horizontally polarized waves to the same extent that they reflect vertically polarized waves, the localizers are designed to radiate waves of the former type. To realize the advantages of horizontal polarization, a special antenna element was developed primarily for localizer use which radiates pure horizontally polarized waves in all directions. The field pattern in the horizontal plane is circular and in the vertical plane is figure-eight-shaped with zero radiation upward. Radiating systems with five antenna elements are used (figure 3), two of which are parasitically driven. The courses produced are entirely free of multiple courses and the bends in any of the courses do not exceed 0.15 degree, which is barely perceptible on the aircraft instrument. This antenna system produces two overlapping field patterns as shown in figure 4 which should give side indications of the guiding path that may be easily located at distances of 20 miles from the airport boundary. The field on one side of the runway center line is modulated at a frequency of 90 cycles per second; on the other side at 150 cycles. A mechanical modulator is used because of its inherent stability and freedom from aging. The courses are straight and reliably stable, maintaining their alignment to within one-tenth degree under all normal weather conditions.

Glide-Path Installation. The glide path is substantially a straight line from an altitude of 1,500 feet at a distance of five miles from the airport to the airport boundary; from there the path is slightly parabolic in shape, intersecting the runway surface at an angle of approximately one degree. The path passes over the outer marker beacon, two miles from the airport boundary, at an altitude between 500 and 700 feet. The method by which the constant-intensity glide path has been produced involves locating the antennas at a considerable distance to one side of the runway and forward along the runway so that the various points along the path appear in different directions as viewed from the antenna (figure 5). In this way, the angle subtended by the glide path, as viewed from the antenna, is opened so that it becomes possible by making

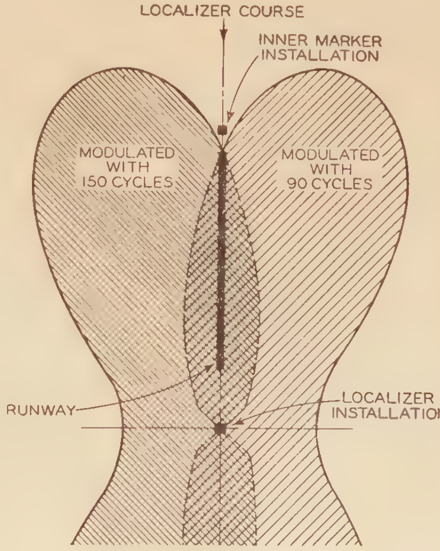


Figure 4. Field patterns from localizer antenna shown in figure 3

the antenna directive in the horizontal plane, to proportion the radiation along the extent of the glide path and control the height of the path at the various points.

The glide-path antenna system consists of two pairs of ultrahigh-frequency loops placed approximately 70 feet apart, fed in the proper phase and amplitude to produce the required pattern. The pair of antennas next to the glide-path-transmitter house, together with their reflecting screen, are shown in figure 6.

The glide-path transmitter is identical in construction and size with the localizer transmitter except that it operates on a frequency of 93.9 megacycles. The output is modulated at a frequency of 60 cycles per second, this modulation being accomplished by applying 60-cycle plate voltage to the two tubes in the output stage.

Marker-Beacon Installations. Five-watt 75-megacycle transmitters produce the marker beacons. Each transmitter and its associated equipment is housed in a small waterproof aluminum enclosure situated alongside of a wire-screen counterpoise 20 feet square over the center of which are two half-wave radiators mounted end to end. The radio-frequency carrier in the outer marker transmitter is modulated at a frequency of 400 cycles per second keyed so as to produce equal-length pulses at the rate of two per second. The inner-marker carrier is modulated at 1,300 cycles and keyed so as to produce equal-length pulses at the rate of six per second.

The marker installations are oriented so that the end-on radiators are parallel to the center line of the runway. In this way the major axis of the elliptically shaped pattern in the horizontal plane is at right angles to, and situated over, the runway center line.

EQUIPMENT ON GROUND—MICRO-WAVE SYSTEM

In general, the micro-wave system is similar to the Indianapolis system, except that the operating frequencies are in the neighborhood of 750 megacycles instead of 100 megacycles as at Indianapolis. Each system, of course, utilizes the best and latest techniques available for use with their respective frequencies. Experimental work with this system has been carried out by Massachusetts Institute of Technology under the sponsorship of the Civil Aeronautics Authority.[2] The experimental apparatus was designed to demonstrate feasibility only, but commercial embodiment of the results is now believed to be within reach of the industry.

The system in its present form uses frequencies of the order of 700 megacycles for both localizer and glide-path beams, although a localizer operating at approximately 400 kilocycles was used in some of the earlier tests conducted by M.I.T.

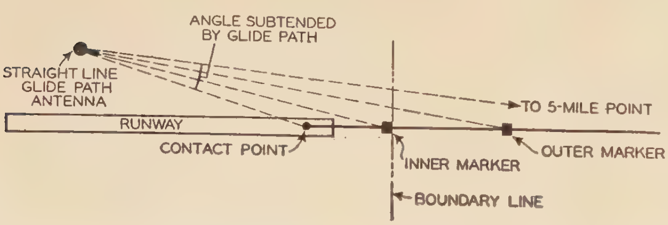


Figure 5. Location of glide-path transmitter and antenna at Indianapolis with respect to runway

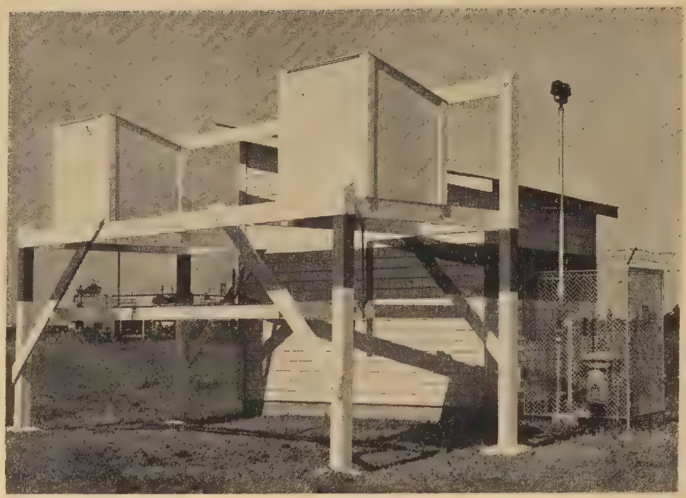


Figure 6. Glide-path transmitter house and antenna array at Indianapolis

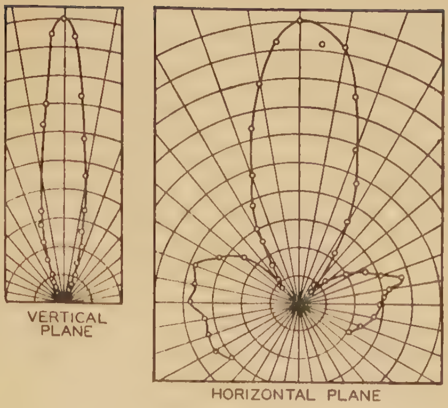
For most of the experimental investigations simple low-powered oscillators were employed as sources, using a feed-back circuit with short sections of coaxial transmission line as circuit elements. These oscillators operated at wave lengths ranging from several meters down to the limit of oscillation of the tube used (about 40 centimeters) delivering about five watts at 50 centimeters and about one watt at 42 centimeters.

A comparative investigation was made of various types of antennas, parabolic reflectors, and horn radiators. On the basis of the results the horn type of radiator was selected because it was simpler to adjust, freer from spurious radiation from feed wires, and had inherently a better radiation pattern than was obtainable from the other devices examined. Like the lower-frequency system, horizontally polarized waves were found to have more uniform behavior with changing ground conditions than vertically polarized waves.

Making use of a theory of design evolved in a separate research program[4] a horn was constructed specifically for the production of a landing beam. The body of the horn was made of three-eighth-inch bakelite-bonded plywood and was lined inside with thin copper foil. Figure 7 shows the completed horn. It is about 26 feet long by 10 feet high by 2.5 feet wide (at the mouth) and has an angle of flare of 20 degrees in the direction of height. At a wave length of 50 centimeters this corresponds to a height of 6 wave lengths and a width of 1.5 wave lengths. The exciting antenna is a straight wire about one-quarter wave length long placed in the throat. Figure 8 shows measured radiation patterns of this horn in the vertical and horizontal planes under substantially free-space conditions. The vertical pattern is notably free from secondary lobes. The horizontal pattern has been made sharp, and the secondary lobes have been tolerated for sake of power gain. The preferred pattern in this plane, were less power gain satisfactory, would have a single broad lobe. A beam of this character could be obtained by reducing the width of the horn.

Figure 7. Electromagnetic horn radiator used in the micro-wave tests

Figure 8. Field patterns in vertical and horizontal planes from the horn shown in figure 7



On the basis of preliminary tests, two horns of the type shown in figure 7 were set up with the lower edges of the mouths touching the ground; the angle of elevation of one was five degrees and of the other ten degrees. When transmitting with equal strength, these two horns yield a glide-path angle of about six degrees; a smaller angle is obtained by reducing the power output or modulation of the lower horn.

In the tests separate transmitters operating at slightly different carrier frequencies and modulated at 90 and 150 cycles per second, respectively, were used to excite the two horns, in order to avoid space interference of the carriers and to obviate any difficulty of cross modulation. Subsequent investigation has established a method by which a single source is used successfully. The use of separate oscillators is open to objection principally because it doubles the transmitting apparatus.

Flight tests made during September 1939 established the straightness of the micro-wave path over its entire length. A straight-line landing path at an angle of about three degrees with the ground was flown consistently over a distance of somewhat more than five miles. Using a transmitter having an estimated power output of 50 watts which was supplied to one horn, flight tests demonstrated that extremely strong signals were received at a distance of 25 miles and an altitude of 2,500 feet. This performance indicates that usable landing signals may be obtained at distances of the order of 50 to 75 miles.

EQUIPMENT ON AIRPLANE—INDIANAPOLIS SYSTEM

As indicated previously, the equipment on the airplane consists essentially of suitable apparatus to receive the three types of signals transmitted from the ground and to translate them into such form as will give visual indications to the pilot to direct him in making the landing. The equipment in most common use combines all three indications on the face of one instrument. The cross-pointer instrument was used in connection with the Indianapolis tests, and a cathode-ray type in the micro-wave tests.

On the cross-pointer instrument (figure 9) the vertical needle is actuated by the signals received from the localizer transmitter and the horizontal needle by those from the glide-path transmitter. When the ship is on course the vertical needle is in the vertical position, right or left displacement indicating that the ship is off course laterally; similarly, the displacement of the horizontal needle above or below horizontal indicates that the ship is respectively below or above the glide-path beam. The indications of both needles are such that when the ship is off course either way it must be shifted in the direction of the needle deflection in order to bring it on course.

Three indicator lights are operated from the output of the marker-beacon receiver. Two of these are used in instrument landing, one to indicate when the plane is over the outer marker and one when it is over the inner marker. The third light shows the pilot when the ship is over one of the fan markers located at important points along airways or over the towers of the radio range transmitting stations which are equipped with cone-of-silence markers (as at *A* in figure 1). The marker-beacon receiver is in continuous operation during the course of a flight, as it has other important uses in addition to its part in the instrument landing procedure.

One antenna, of the horizontal ultrahigh-frequency loop type, receives both runway localizer and glide-path signals. A horizontal dipole antenna mounted underneath the plane receives the marker-beacon signals.

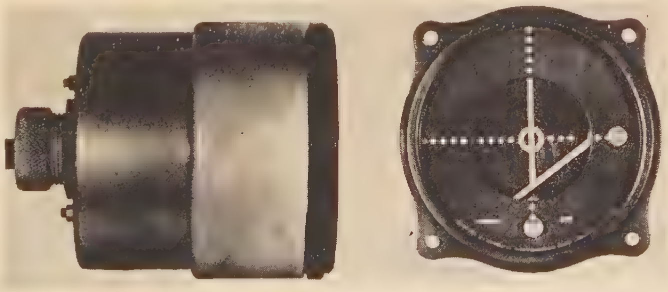


Figure 9. Cross-pointer instrument

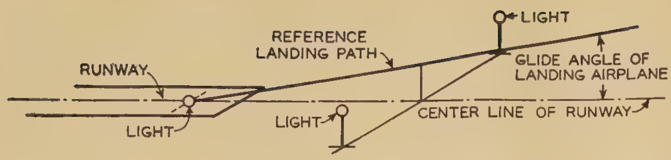


Figure 10. Hypothetical arrangement of lights on landing field representing basis of micro-wave indicating instrument

Both localizer and glide-path receivers are crystal-controlled fixed-frequency superheterodyne units. The localizer receiver is equipped with automatic volume control. To assure satisfactory operation under varying conditions, the glide-path receiver is provided with a voltage regulator, a ballast lamp, and temperature-sensitive elements.

The marker-beacon receiver also is a crystal-controlled fixed-frequency superheterodyne unit, and is arranged for both visual and aural indication of the signal being received. Three filters in the receiver separate the 400- and 1,300-cycle modulating tones of the instrument landing system, and the 3,000-cycle tone of the fan and cone-of-silence markers.

EQUIPMENT ON AIRPLANE—MICRO-WAVE SYSTEM

In developing a suitable instrument for the micro-wave system to be installed on the airplane, the problem was considered as illustrated in figure 10. If under conditions of no visibility it were possible to present to the pilot the same information that he would obtain were he to land on a clear night by means of three lights arranged on the landing field as shown, then a serviceable instrument landing system could be realized. These lights would indicate to the pilot in a simple, natural, and continuous manner not only the location but also the attitude and heading of his ship.

This conception of the problem is due to Doctor Irving Metcalf of the Civil Aeronautics Authority, and is responsible in part for the undertaking of the micro-wave instrument-landing research by M.I.T., in that it demands much greater precision in the location of an approach path than appeared possible with the then-existing glide-path systems.

To visualize the problem in greater detail imagine that the three lights are seen through a transparent screen in front of the pilot. Assume that the screen has vertical and horizontal crosshairs intersecting at its center. When the airplane is in the proper orientation for landing, and is on the reference landing path defined by the three lights as shown, the pilot sees these lights equally spaced along the horizontal crosshair, the center light coinciding with the center of the screen. Any departure of the lights from this pattern on the screen indicates a corresponding departure of the airplane from the proper location or orientation.

In the simplest interpretation, the location of the light group indicates orientation and the relative configuration of the lights as a group indicates location. Thus turning of the airplane to the right or left moves the lights as a group left or right respectively; moving to the right or left of the reference landing path moves the image of the center light nearer to the image of the right- or left-hand light, respectively.

In the instrument developed, the cathode-ray tube is used to provide the indications. Information regarding orientation is derived from gyroscopic instruments on the

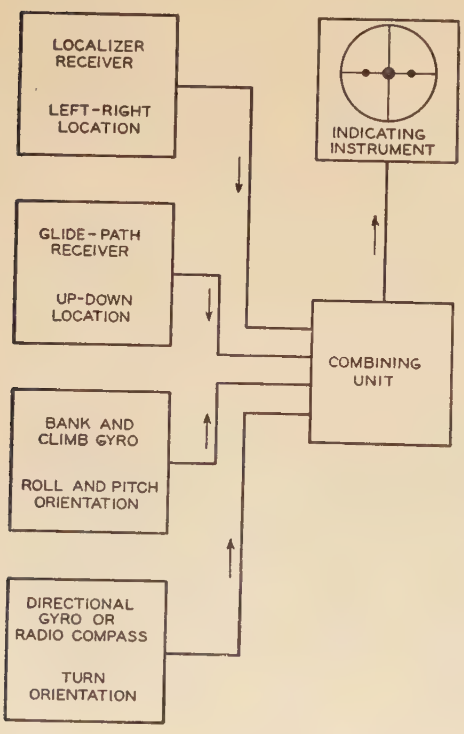


Figure 11. Block diagram showing method of combining indications from four sources to give a composite pattern on the micro-wave-system instrument

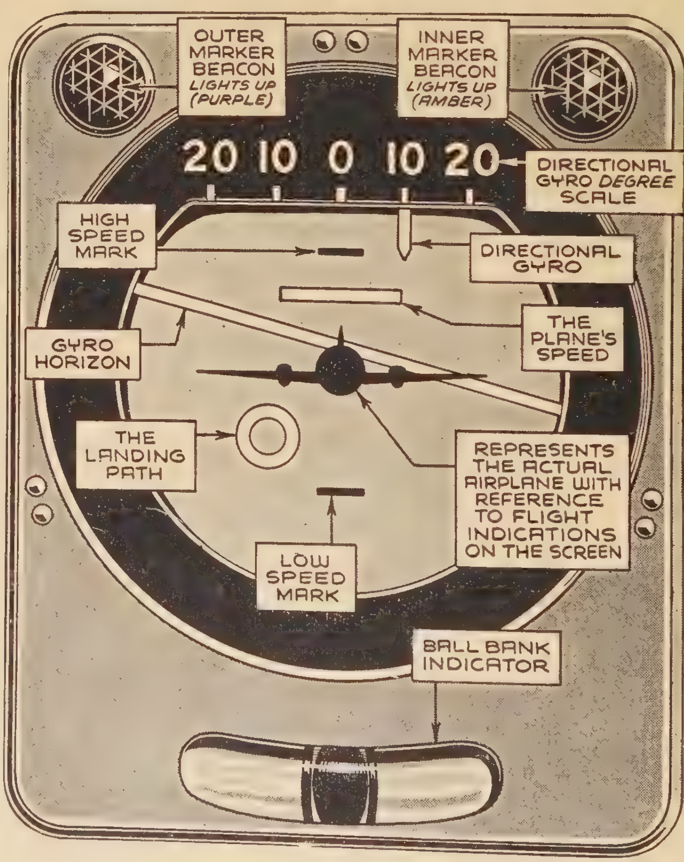


Figure 12. Face of Flightray instrument showing the various indications

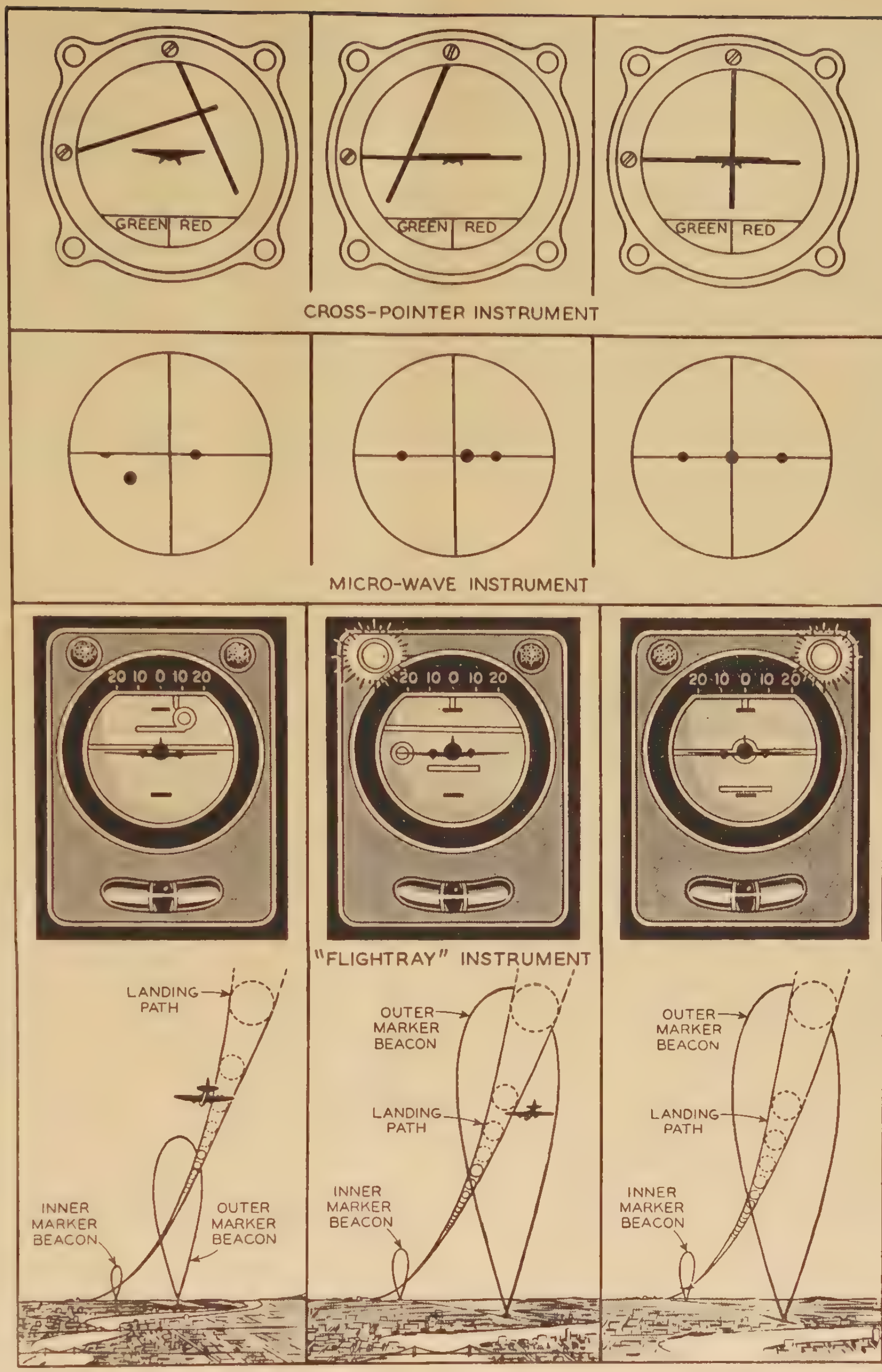
Figure 13. Typical indications on the three types of instruments described

Separate signal lights associated with the cross-pointer and micro-wave instruments indicate when the outer and inner marker beacons are passed

Left: Pilot is starting an instrument landing; ship below and to left of glide path

Center: Ship off path to right and beginning to descend; also passing outer marker beacon

Right: Ship on glide path and passing inner marker beacon; has but about one-half mile to airport runway



airplane; information regarding location is derived from the radio beams transmitted from the ground. The various indications are combined as shown in figure 11, and through a mechanical commutating device are impressed in rapid succession on the deflecting plates of a single-gun cathode-ray tube so as to give the visual appearance of a stationary pattern on the screen of the tube.

To obtain suitable indications from the gyroscopic instruments required the development of a simple electrical takeoff. Voltages thus obtained from the gyro instruments are sufficient to deflect the spots on the cathode-ray tube directly, and therefore amplifiers are not necessary.

The ultrahigh frequencies used necessitated the development of special equipment to receive the glide-path signals on the airplane. The received signal goes directly into a converter which mixes the signal with the third harmonic of the local 230-megacycle oscillator, producing a 10-megacycle beat-frequency signal. The beat frequency is fed to the intermediate-frequency amplifier where it is amplified with no greater difficulty than any other 10-megacycle signal. In the tests, an elaborate audio-frequency amplifier followed the superheterodyne receiver proper, incorporating four stages of resistance-coupled amplification with automatic volume control, a separating filter for 90 and 150 cycles per second, and separate one-stage amplifiers following the filter. The output of this audio unit is fed to the adapter unit of the cathode-ray indicator.

A control is provided to allow adjustment of the relative gain of the two audio channels. The setting of this control determines the angle of the glide path with respect to the ground, and the control may be set so that the approach-path angle is correct for a given type of airplane. This arrangement does not require a readjustment of the ground station to set the glide angle. The antenna is of the coaxial type, connected to the receiver by a one-quarter-inch copper coaxial line.

The cathode-ray indicating instrument also is useful during flight, the runway localizer signals simply being replaced by radio-beacon signals. It can be applied also to other landing systems; likewise, the micro-wave glide-path and localizer equipment can be used with other indicators, such as the conventional cross-pointer instrument.

THE FLIGHTRAY

Another cathode-ray instrument, developed by the Sperry Gyroscope Company for both instrument flight and landing, is known as the Flightray[3] (figure 12). When

used in making instrument landings, the localizer landing beam is arranged to control the horizontal position of the landing-path circle and the glide-path beam the vertical position. In flight, the horizontal position of the circle is controlled by the flight-course radio beacon, and the vertical position by a barometric altimeter. In either event, the ship is on course when this circle rings the fuselage of the miniature airplane outline in the center of the screen.

Attitude information is obtained from the gyroscopic instruments by means of simple electromagnetic pickups. As a knowledge of speed is important in making an instrument landing, an indication of the plane's speed also is provided, by a short horizontal line, the position of which varies vertically between two limit marks on the screen. When this horizontal line approaches the low-speed mark, the pilot knows that his ship is approaching its stalling speed.

The position of the miniature airplane outline painted on the screen of the cathode-ray tube indicates the position of the plane with respect to each of the four indications. When the plane is off course in any direction, it need only be flown toward the particular pattern to bring it back on course. Signal lights above the cathode-ray tube indicate when the ship passes over the outer and inner markers, one indicator for each marker.

As there are four separate indications on the face of the cathode-ray tube, switching is necessary, as with the instrument used in the micro-wave tests. To accomplish this, the various amplifiers associated with each instrument pickup are sequentially made operative by means of a commutator which applies suitable control voltages to each amplifier in turn. As with the micro-wave system, commutation takes place at a rate well above the persistence of human vision, with the result that although only one line is shown at a time the composite pattern is entirely free from flicker.

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Capacitors on a Growing System

THE capacitor is a very useful addition to the group of equipments and materials used on an electric distribution system. Its greatest value is that it increases the capacity of circuits carrying reactive load currents. A complete study of the optimum balance between capacitors and new circuit capacity also involves a study of saving in copper losses, improvement in voltage, which may or may not increase revenue, and a consideration of such factors as new emergency tie capacity that may be provided by a new circuit.

The increase in circuit capacity on any part of a power system resulting from capacitors, should not be valued as new capacity unless it will be necessary within a period of several years. There should be some tangible saving or postponement of investment for some definite period of time in any part of the system where increase in capacity is valued as such. Unless this is true, the saving in copper losses and any desirable voltage improvement are the only immediate benefits.

When evaluating saving in losses in the parts of the system where the increase in capacity is evaluated, the saving in losses from circuit additions should also be taken into account. When put on the basis of equal increases in circuit capacity, the increase obtained with a new circuit will save 50 to 60 per cent as much of the losses as that obtained with capacitors. For capacitors connected to a circuit at all times, the saving in losses may be readily estimated from a group of curves without knowing the original losses. The only characteristics of the load that need be known are the reactive kilovolt-ampere-hours supplied by a circuit and the approximate distribution of the reactive kilovolt-ampere load along that circuit. The saving in losses in a feeder main from three equal capacitor units will be within a few per cent of the saving when capacitors of the same total rating are distributed along the feeder main in the same way as the reactive load.

The possible increase in revenue will be small on a well-regulated system. In those extreme cases where the feeder is so long that regulators cannot maintain acceptable voltage at all points, the increase in voltage to make it satisfactory will be more important than the increase in revenue. Unless some special provision is made for control, a static capacitor has an effect on voltage at any point similar to that of a fixed booster. The fixed boost can usually be obtained with a fixed booster at a much lower cost. Capacitors, however, may be installed in preference to other system additions because they serve several functions whereas the alternative circuit additions serve only one purpose.

A study of some typical areas and loads indicates that the improvement of power factor with fixed capacitors on four-kilovolt feeders, to an ultimate value of 85 to 95 per cent will be justified. The higher power factor, in general, will apply to outlying residential areas, and the lower power factor, in general, to areas that are predominantly industrial.

On a large power system for the immediate correction of power factor to these limits in most cases would require a major investment which would not yield an immediate return. If capacitors are added to the power system as load in certain areas makes an increase of capacity necessary, they provide an effective means of adding capacity in small increments. These units will then be paying their way at all times until the optimum economic balance between investment in capacitors and other equipment is reached.

"Conclusion" of the first James H. McGraw Prize Paper for 1940 of the Edison Electric Institute, "Basis for a Program of Capacitor Additions on a Growing Distribution System," by V. G. Rettig (A'32), and published in the EEI *Bulletin*, August 1940, pages 387–94.

Some Notes on the 1940 National Electrical Code

ALVAH SMALL
MEMBER AIEE

Revised tabulations of allowable current-carrying capacities of conductors are among the many significant changes in the new 1940 edition of the National Electrical Code.* In this especially prepared statement, the chairman of the committee responsible for compiling the Code discusses these and other significant changes embodied in the new edition.

THE 1940 edition of the National Electrical Code, approved August 7 as an American Standard, is now being distributed; the indicated effective date is November 1. The publisher, the National Board of Fire Underwriters, expects a demand for over 300,000 copies, making this edition the "best seller" of the whole series of 21 editions beginning with the original 1897 text.

Recently it was claimed that in more than 650 political jurisdictions, state laws or municipal ordinances currently in force specify that wiring of premises for light, heat, and power must be installed according to the Code. In many other jurisdictions the Code is the basic text for local wiring regulations.

No important change was made in the editorial plan of the Code first used in the preceding (1937) edition; the chapter and article arrangement of that edition is continued except that the contents of chapters 9 and 10 have been transposed, the latter now containing tables and diagrams, and chapter 9 containing the few construction rules, so-called, thus far adopted.

A detailed analysis, listing all changes from the text of the 1937 edition, has been prepared by and can be obtained from the National Electrical Manufacturers Association (155 East 44th Street, New York, N. Y.). Many of the changes do not greatly modify the substance of the previous Code provisions. Quite a number of the changes are only to improve cross references.

Nevertheless, there are certain important changes of significance to those who supply, install, and employ electricity and utilization equipment. This brief article discusses some of these changes in the order of their appearance in the 1940 Code and without attempting evaluation of technical or economic importance.

The statement of the scope of the Code now excludes railways, as well as other utilities, so that the Code is not to be applied to electrical installations in railway property that are for facilities and purposes peculiar to the exercise of the utility function of the railway.

Several new definitions and changes in former ones add to clarity in applying some of the rules. It is the intent otherwise to employ the "Standard Electrical Definitions" and to have them apply throughout.

Details given in article 110, section 1111, as to working space about low-voltage equipment, indicate clearly that the Code deals also with the personal-injury hazard and not with the fire hazard only. In general, the intent was to have all the personal-injury safeguarding requirements of the National Electrical Safety Code for utilization wiring and equipment appear also in this edition of the National Electrical Code.

New section 1116 records another step in recognizing the use of mechanical devices, in lieu of or in addition to soldering, as a standard method for making conductor joints, taps, and terminals.

A number of changes in article 210, while adopted to secure safeguarding of a fire or casualty hazard, nevertheless, will bear importantly on the matter of adequacy of the installation as a whole. The Code proceeds conservatively in applying the police power in providing for adequacy for future uses of electricity.

In article 240 "Overcurrent Protection," paragraphs 2451–3 forecast general use by November 1, 1941, of a tamper-resisting, so-called type *S*, plug fuse, the products of all makers to be interchangeable.

Article 300 of chapter 3, "Wiring Methods and Materials," and related texts and tables in chapters 9 and 10, recognize three grades of rubber insulation for conductors of feeder and branch circuits. The classification is according to the operating temperature of the conductors. So-called code-grade rubber insulation (type *R*) is not to be employed where subject to temperatures higher than 50 degrees centigrade. This is the ambient-temperature limit specified in previous editions for whatever grade of rubber insulation was employed. The two new grades of rubber, types *RP* and *RH*, may be used with conductor operating temperatures of 60 and 75 degrees centigrade, respectively. They correspond generally to the performance and heat-resistant grades of rubber insulation that have been promoted for some years, but without Code recognition of their special properties.

CURRENT-CARRYING CAPACITIES

The familiar table 1, "Allowable Current-Carrying Capacities of Conductors," of previous editions of the Code is dropped. New tables 1 and 2 list current values for various sizes of conductors with these three grades of rubber insulation and for five other recognized classes of conductor insulation that may be employed in one or several of the standard wiring methods. Table 1 applies for three conductors in a raceway with two correction factors to be applied when a raceway contains up to six

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*Copies of the 1940 edition of the National Electrical Code (ASA designation No. *C*1-1940) are available at five cents each from the American Standards Association, 29 West 39th St., New York, N. Y.

or up to nine conductors, respectively. Table 2 applies to single conductors in free air. Both tables assume a room temperature of 30 degrees centigrade and correction factors are given for higher room temperatures, up to 140 degrees centigrade when asbestos is the principal component of the insulation.

This recognition of new grades of rubber insulation and the revised allowable current-carrying capacities of conductors are the products of investigations made under the auspices of a technical committee of the rubber building wire group of National Electrical Manufacturers Association, the initial and basic report of which is an AIEE paper by S. J. Rosch (AIEE TRANSACTIONS, volume 57, 1938, pages 155–67).

A notable change is the reduced allowable current-carrying capacities for conductors with code-grade rubber insulation and larger than 1,000,000 circular mils "in free air" and larger than number 8 AWG in raceways. These reductions contemplate "continuous" loads of the named values, a condition much more probable in modern wiring practice than was presumed with old table 1, whatever wiring method was employed.

The new tables 1 and 2, as was the case with former table 1, takes no account of voltage drop. Obviously, those laying out wiring systems must allow for it, especially when the calculated current loads on conductors produce operating temperatures approaching the permitted limits.

THIN-INSULATED CONDUCTORS FOR REWIRING

Present-day trends for improved illumination, especially in industrial and commercial occupancies, and the prohibitive cost of rewiring in some existing premises are recognized in paragraph (*e*) of section 3005 which allows: "Where in rewiring for increased load, space is not available in raceways" for conductors having standard thicknesses of insulation "and it is impracticable to increase the size of the raceway due to structural conditions," thin-insulated conductors with rubber insulation of the performance (type *RPT*) or the heat-resistant (type *RHT*) grades may be used; these insulations may be 1/32 inch instead of 3/64 inch in thickness for numbers 14 to 10 wire, inclusive—a reduction of 33 per cent. In addition, for the same small conductor sizes, the latex type of rubber insulation (type *RU*) that is not less than 0.018 inch thick may be used. This type of insulation is accepted for conductor operating temperatures not exceeding 60 degrees centigrade.

For these special conditions, paragraph (*e*) of section 3005 also recognizes conductors having "a flame-retardant, moisture-resistant approved solid synthetic insulation (type *SN*)" with a temperature limitation of 60 degrees centigrade in numbers 14 to 4/0, with an insulation thickness as shown in table in section 93001, no outer fibrous covering being required. The insulation thicknesses called for in this table are:

Conductor size (AWG number)	14–10	8	6–2	1–4/0
Insulation thickness (inch)	2/64	3/64	4/64	5/64

Except for numbers 6–2 these values are, in each case, 1/32 inch less (on the radius) than for rubber insulation on types *R*, *RP*, and *RH* wires. The omission of the fibrous covering further reduces the over-all diameter and cross-section area for a given size of conductor.

Another change provides recognition in numbers 14–8, inclusive, of conductors having the heat-resistant grade of rubber insulation (type *RHT*) 1/64 inch less (on the radius) in thickness than for types *R*, *RP*, or *RH* insulations and for general use wherever wires of these types are acceptable.

The foregoing changes recognizing new grades and reduced thickness of rubber insulation explains the requirement in paragraph (*f*) of section 3005 that "all rubber-covered conductors shall have a readily identifiable permanent marking to indicate the type of insulation."

Other articles in chapter 3 apply to specific methods of wiring. Former articles 326, "Surface Wooden Raceways," and 330, "Cast-in-Place Raceways," have been dropped. A new wiring method utilizing the hollow spaces in cellular steel floor construction is covered by the ten paragraphs of new article 356.

From 1897 to 1911 inclusive the National Electrical Code was produced under the auspices of the Underwriters National Electric Association. The 1913 and all subsequent editions have been sponsored by the National Fire Protection Association, which took over when the original sponsor was dissolved. The actual work of considering proposals for changes in the Code is in charge of the electrical committee, one of more than 40 technical committees of the NFPA. Beginning with the 1925 edition, the electrical committee has been so organized as to qualify as a sectional committee of the American Standards Association. Most editions of the National Electrical Code, beginning with that of 1920, have been approved American Standards.

From its large and varied membership, the National Fire Protection Association appoints members and alternates for service on the electrical committee representative of a cross section of the electrical industry concerned with its provisions. Over 100 such delegates were in attendance at the session in December 1939 when five morning and afternoon and three evening meetings were required to consider and act upon reports from over 60 subcommittees.

During May 1940, the committee's report was accepted by the National Fire Protection Association, which formally adopted the text of the 1940 edition of the Code as an Association Standard. This Standard was approved August 7 as an American Standard.

AIEE PARTICIPATION

The American Institute of Electrical Engineers has participated in the compilation of the Code with membership in the electrical committee since the National Fire Protection Association became the sponsor in 1913, and was previously a member of the so-called conference which reviewed the editions published by the Underwriters' National Electric Association. Members F. V. Magalhaes and H. S. Warren take important and constructive parts in the electrical-committee proceedings as AIEE representatives. In addition, many other members of the committee are AIEE members.

Nomography for the Electrical Engineer

GUIDO E. FERRARA
ENROLLED STUDENT AIEE

An outline of basic principles underlying nomographic charts, supplemented by examples illustrating their application to electrical-engineering problems

A RELATIVELY large amount of the work of calculation done by the engineer, designer, and student, consists of the repeated application of a certain number of formulas satisfying different conditions. When the number of variables entering into the calculation is large, or when the variables are raised to fractional powers, the difficulties and time involved may become very great. This process of repeated substitution can be greatly simplified by the use of nomographic charts.

A nomographic chart is the representation of an equation or formula in such a way as to provide a simple solution by simple mechanical means. Few books have been written on the subject, and articles appearing in technical publications have been restricted more or less to the presentation of just one particular formula. The fact is that the science of nomography is rather new—d'Ocagne (1884) gave it its name and developed the process of collinear points.

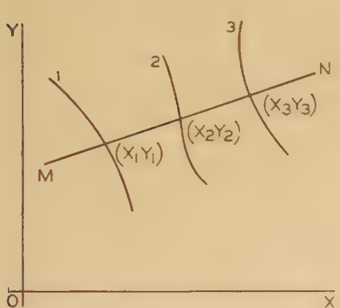

Figure 1

The utility and convenience of nomographic charts is obvious from the following brief summary of their principal advantages:

1. The number and variety of problems to which they can be applied is quite large.

2. There is no difficulty when the number of variables is large, or when the variables are raised to fractional powers.

3. Once the chart for any particular problem has been prepared, chances for errors are minimized.

4. The charts are simple and certain in use, so that calculations can be left to the care of unskilled subordinates.

PRELIMINARY THEORY

The mathematical foundation of nomography rests on the elementary theory of the third-order determinants. In the study of analytic geometry, a geometrical meaning was given to a third-order determinant. In figure 1, the line MN intersects the three curves 1, 2, 3, at points whose co-ordinates are (X_1Y_1), (X_2Y_2), (X_3Y_3). By similar triangles,

$$\frac{Y_2-Y_1}{X_2-X_1}=\frac{Y_3-Y_1}{X_3-X_1} \tag{1}$$

Or

$$Y_1X_2+Y_2X_3+Y_3X_1-Y_2X_1-Y_3X_2-Y_1X_3=0 \tag{2}$$

But, from algebra, it can be shown that equation 2 is the expansion of the third-order determinant

$$\begin{vmatrix} X_1 & Y_1 & 1 \\ X_2 & Y_2 & 1 \\ X_3 & Y_3 & 1 \end{vmatrix}=0 \tag{3}$$

whence the theorem: If a third-order determinant has the value of 0 then the points (X_1Y_1), (X_2Y_2), (X_3Y_3) are collinear.

It is obvious then, that any equation which can be transformed into a form identical with equation 3 can be represented and solved by a nomographic chart.

EXAMPLES

Consider the equation

$$2x=3y+z \tag{4}$$

which can be written as a third-order determinant thus:

$$\begin{vmatrix} z & 0 & 1 \\ y & 1 & 0 \\ 2x & 3 & 1 \end{vmatrix}=0 \tag{5}$$

This determinant is not in the form of equation 3. It can be transformed, though, if one remembers a few fundamental theorems involving determinants, thus:

$$\begin{vmatrix} z & 0 & 1+0 \\ y & 1 & 0+1 \\ 2x & 3 & 1+3 \end{vmatrix}=\begin{vmatrix} 0 & z & 1 \\ 1 & y & 1 \\ 3/4 & x/2 & 1 \end{vmatrix}=0 \tag{6}$$

In this last form, the determinant is in nomographic-form arrangement. It can be seen that every set of values of z, y, and x satisfying equation 6 must have corresponding collinear points. Hence, the abscissa of z is 0, that of y is 1, and that of x is 3/4. The corresponding ordinates are the values of z, y, and x. So if the graduations of z and y are the same, then those of x are 1/2.

The nomograph corresponding to equation 6 is shown in figure 2. Any straight line drawn across the three scales intersects values of x, y, and z which satisfy the equation: $2x=3y+z$.

The same theory can be applied to equations in which

Essential substance of a paper presented at a student session of the AIEE Great Lakes District meeting, Minneapolis, Minn., September 28–30, 1939.

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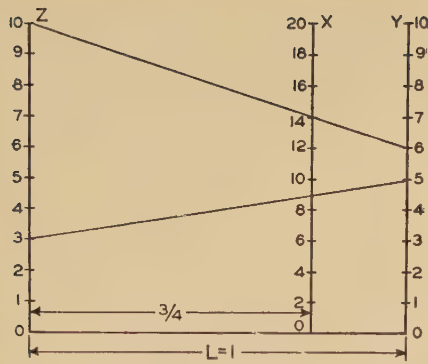


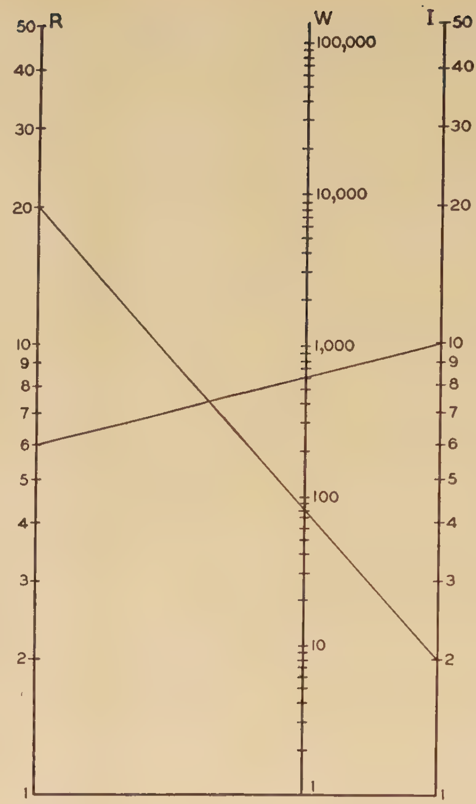


Figure 2 (above). Nomograph for equation $2x=3y+z$

Figure 3 (right). Nomograph for equation $W=I^2R$

products or quotients are involved, for example, the familiar equation:

$$W=I^2R \tag{7}$$

This equation can be written also as:

$$\log W=2\log I+\log R \tag{8}$$

Equation 8 may be expanded into a third-order determinant thus:

$$\begin{vmatrix} \text{Log } R & 0 & 1 \\ \text{Log } I & 1 & 0 \\ \text{Log } W & 2 & 1 \end{vmatrix}=0$$

or

$$\begin{vmatrix} \text{Log } R & 0 & 1 \\ \text{Log } I & 1 & 1 \\ \text{Log } W & 2 & 3 \end{vmatrix}=\begin{vmatrix} 0 & \text{Log } R & 1 \\ 1 & \text{Log } I & 1 \\ 2/3 & \dfrac{\text{Log } W}{3} & 1 \end{vmatrix}=0 \tag{9}$$

Instead of using the linear scale for the ordinates of the variables, now a logarithmic scale should be used. The resulting nomograph is shown in figure 3.

Note that the graduations of I and R are three times as large as that of W. A little thought will show how to arrange the expanded determinant so as to get W on a different scale.

As a further example, the nomograph for the equation

$$Z^2=R^2+X^2 \tag{10}$$

has been constructed. This equation is familiar to the electrical engineer, Z representing the impedance of the circuit, R the ohmic resistance, and X the effective reactance.

It can be expanded into a third-order determinant, and put into nomographic form thus:

$$\begin{vmatrix} R^2 & 0 & 1 \\ X^2 & 1 & 0 \\ Z^2 & 1 & 1 \end{vmatrix}=\begin{vmatrix} 0 & R^2 & 1 \\ 1 & X^2 & 1 \\ 1/2 & 1/2Z^2 & 1 \end{vmatrix}=0 \tag{11}$$

In this case, the scale used on the ordinate of the variables is a "square" scale, the first interval being 1, the second 4, the third 9, etc.

The nomograph for equation 10 is shown in figure 4.

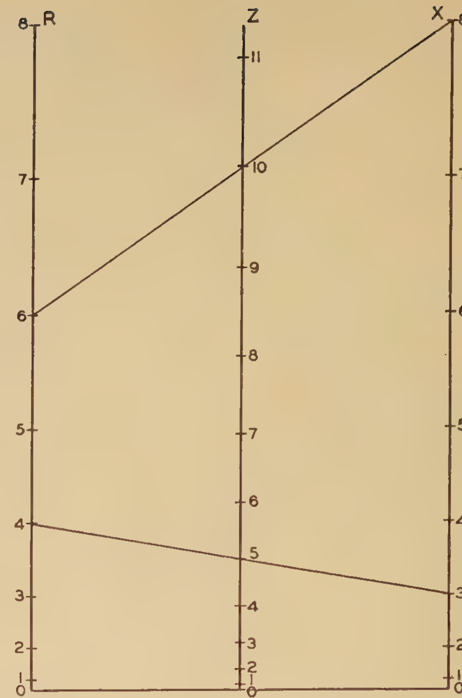


Figure 4. Nomograph for equation $Z^2=R^2+X^2$

The values of the abscissas for the three variables are given in equation 11. The scale of Z is in this case 1/2 that of X and R.

N CHARTS, OR COMBINATION OF NOMOGRAPHS

Consider the fundamental electric-motor equation

$$V_t=E_g+I_aR_a \tag{12}$$

in which V_t represents the terminal voltage, E_g the counter (or generated) electromotive force, and I_aR_a the armature voltage drop. This is a combination of equations 4 and 7 so that if we let

$$E_d=I_aR_a \tag{13}$$

the resultant equation is:

$$V_t=E_g+E_d \tag{14}$$

If we try to combine these two equations into a nomograph we can see at once that equation 13 yields results on a log scale while equation 14 yields results on a linear scale. Hence it is not advisable to construct a monograph for equation 13 by the method shown for equation 7. But equation 13 can be written in a third-determinant form thus:

$$\begin{vmatrix} R_a & 1 & 0 \\ 0 & I_a & 1 \\ -E_d & 0 & 1 \end{vmatrix}=\begin{vmatrix} R_a & 1 & 1 \\ 0 & \dfrac{I_a}{1+I_a} & 1 \\ -E_d & 0 & 1 \end{vmatrix}=\begin{vmatrix} 1 & R_a & 1 \\ \dfrac{I_a}{1+I_a} & 0 & 1 \\ 0 & -E_d & 1 \end{vmatrix}=0 \tag{15}$$

From the last determinant expression it can be seen that the abscissa of R_a is 1; those of I_a are $I_a/1+I_a$; and that of E_d is 0. Also, the ordinate of I_a is 0, which means that I_a lies on the X axis. Notice that E_d is negative; therefore it is plotted in the opposite direction from that of R_a. For sake of compactness we may plot the diagram on oblique axes with R_a and E_d in opposite directions,

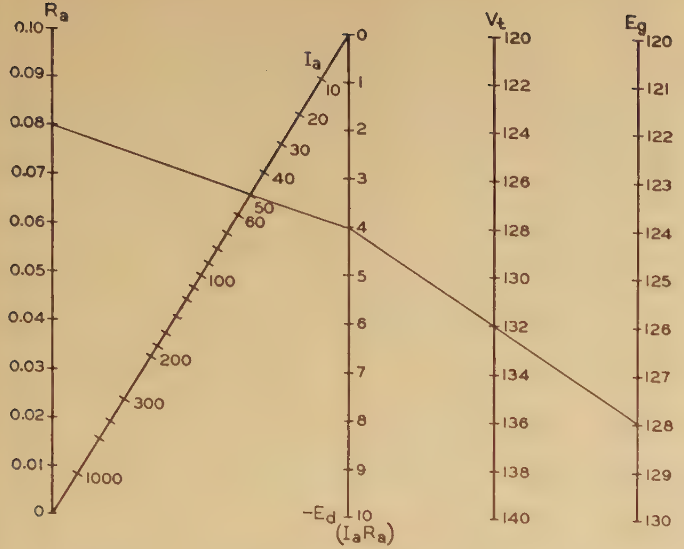


Figure 5. Nomograph for equation $V_t = E_g + I_a R_a$

and the zero points of R_a and E_d are joined by a diagonal. The graduations on this diagonal are projections of the abscissa $X_{I_a} = I_a/(1+I_a)$ which are laid off on the horizontal. The two nomographs are combined as shown in figure 5.

EQUATIONS WITH MORE THAN THREE VARIABLES

The method used in the foregoing examples can be applied to linear equations with more than three variables. Consider the equation of inductance L of a coil, given in terms of turns N, core permeability μ, area A, and length l:

$$L = \frac{4\pi N^2 \mu A}{10^9 l} \tag{16}$$

which can be written:

$$\log L = \log \frac{4\pi}{10^9} + 2 \log N + \log \mu + \log A - \log l \tag{17}$$

Let

$$\log X = \log \frac{4\pi}{10^9} + 2 \log N + \log \mu \tag{18}$$

and

$$\log Y = \log A - \log l \tag{19}$$

Then:

$$\log L = \log x + \log Y \tag{20}$$

If equation 18 is expanded as a determinant, we can construct a nomograph and determine X. If the same process is used on equation 19 the resultant will be Y. Now if X and Y are plotted in series as given by equation 20, the final solution of L is obtained. For equation 18 we obtain:

$$\begin{vmatrix} \left(\text{Log } X - \text{Log } \dfrac{4\pi}{10^9}\right) & 1 & 1 \\ 2 \text{ Log } N & 1 & 0 \\ \text{Log } \mu & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0 & \text{Log } \mu & 1 \\ 1 & 2 \text{ Log } N & 1 \\ {}^1/_2 & {}^1/_2\left(\text{Log } X - \text{Log } \dfrac{4\pi}{10^9}\right) & 1 \end{vmatrix} = 0 \tag{21}$$

For equation 19 we obtain:

$$\begin{vmatrix} \text{Log } Y & 1 & 1 \\ -\text{Log } l & 1 & 0 \\ \text{Log } A & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0 & \text{Log } A & 1 \\ 1 & -\text{Log } l & 1 \\ {}^1/_2 & {}^1/_2 \text{ Log } Y & 1 \end{vmatrix} = 0 \tag{22}$$

Also for equation 20:

$$\begin{vmatrix} \text{Log } L & 1 & 1 \\ \text{Log } X & 1 & 0 \\ \text{Log } Y & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0 & \text{Log } Y & 1 \\ 1 & \text{Log } X & 1 \\ {}^1/_2 & {}^1/_2 \text{ Log } L & 1 \end{vmatrix} = 0 \tag{23}$$

The nomographs for X and Y are plotted separately, and from them the resultant combination for equation 23 is constructed. The complete chart is shown in figure 6. Note that the X and Y axes are not graduated because they serve solely for the purpose of reference. Note also

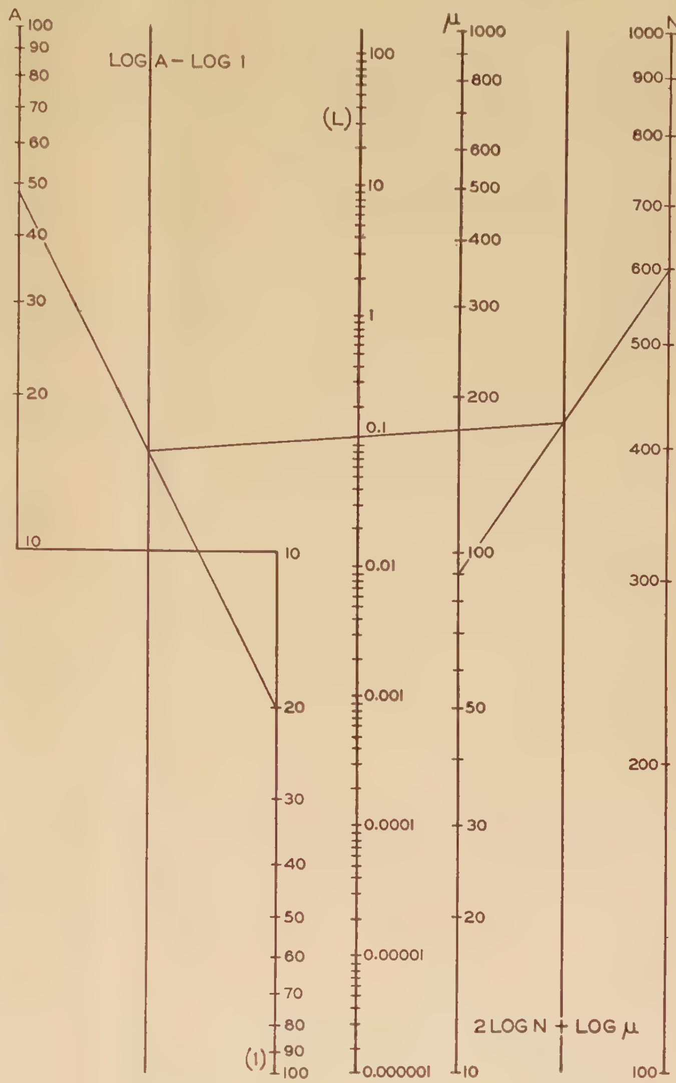


Figure 6. Nomograph for equation $L = \dfrac{4\pi N^2 \mu A}{10^9 l}$

that the constant log $(4\pi/10^9)$ was taken care of on the X axis. In fact, it did disappear there because the X axis is not graduated. The reader can analyze the complete chart and discover for himself that the same process can be applied to an equation involving any number of variables.

In order to graduate the scale of L, the following scheme was used: When the inductance is 1 henry, the turns 1,000, μ 500, and area 10, then the length is 62.83. Connect N and μ, and also A and l—(l is 62.83). Now connect the point of intersection on X with the point of intersection on Y, and where the line crosses the axis L mark 1

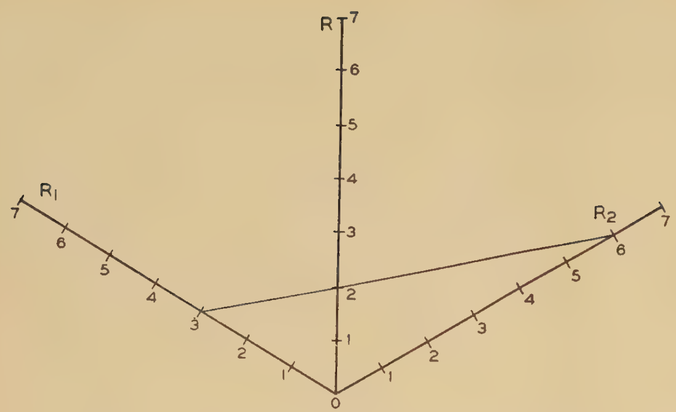


Figure 7. Nomograph for equation $R=\dfrac{R_1R_2}{R_1+R_2}$

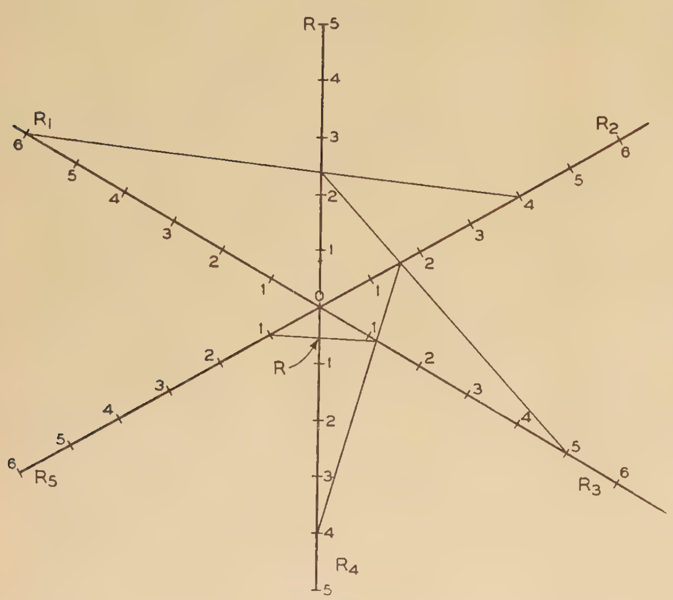


Figure 8. Nomograph for equation $\dfrac{1}{R}=\dfrac{1}{R_1}+\dfrac{1}{R_2}+\dfrac{1}{R_3}+\dfrac{1}{R_4}+\dfrac{1}{R_5}$

henry. Then the rest of the graduation can be completed above and below this point.

CONCURRENT LINE CHARTS

This type of chart is one of the most interesting, especially for the undergraduate electrical engineer. It applies to equations in the form:

$$\frac{1}{R_1}+\frac{1}{R_2}=\frac{1}{R} \tag{24}$$

where R is the effective resistance across R_1 and R_2 in parallel. Rewriting the equation as $R_1R+R_2R=R_1R_2$ and expanding it into a determinant:

$$\begin{vmatrix} R_1 & 0 & 1 \\ 0 & R_2 & 1 \\ R & R & 1 \end{vmatrix} = \begin{vmatrix} 0 & R_1 & 1 \\ R_2 & 0 & 1 \\ R & R & 1 \end{vmatrix} = 0$$

we see that R is at an angle of 45 degrees with R_2 and R_1. By simple geometry, it can be proved that when the angle between R_1 and R_2 is 120 degrees with R bisecting this angle, the units of each axis may be made the same.

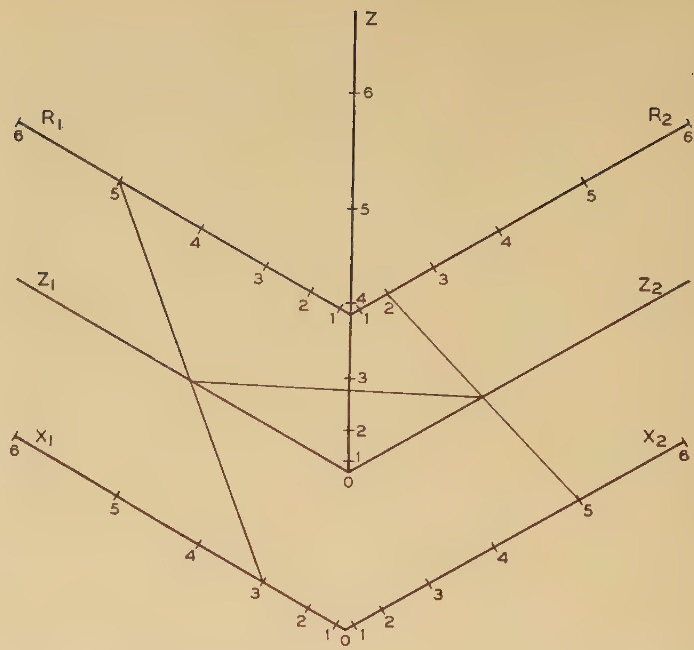


Figure 9. Nomograph for equation

$$Z=\frac{\sqrt{R_1^2+X_1^2}\ \sqrt{R_2^2+X_2^2}}{\sqrt{R_1^2+X_1^2}+\sqrt{R_2^2+X_2^2}}$$

Figure 7 shows the nomograph for two resistances in parallel. Figure 8 shows the same nomograph to be used when more than two resistances are in parallel.

Figure 9 represents an interesting combination of parallel-axes and concurrent-axes nomographs. The parallel-axes example of equation 10 was combined with the last method, so that one can solve for the impedances of each branch and obtain the value of the parallel combination with just one mechanical operation.

SUMMARY OF PROCEDURE

The foregoing examples show that the whole theory of nomography is embraced in the basic theory of third-order determinants. In order to apply this theory to the practical construction of nomographs, the following requirements should be satisfied:

1. Reduce the equation of a number of variables into one of only 3 variables.
2. Express the equation as a third-order determinant.
3. By proper manipulation arrange the determinant into another of nomographic form.
4. Represent the determinant by means of abscissas and ordinates properly scaled.

If the processes used in the foregoing examples are thoroughly understood, they should be sufficient to cover many of the common formulas used by the electrical engineer.

RELATED LITERATURE

1. The Elements of Nomography, **Leon S. Johnston.** University of Detroit (Mich.) Press, 1936.
2. The Construction of Graphical Charts, **John B. Peddle.** McGraw-Hill Book Company, New York, 1910.
3. The Construction of Nomographic Charts, **F. T. Mavis.** International Textbook Company, Scranton, Pa., 1939.
4. Alignment Charts, **W. J. Kearton, George Wood.** Charles Griffin Company, London, 1932.

Institute Activities

A Wish For
A Merry Christmas and a Happy New Year
From President Royal W. Sorensen

"A Merry Christmas and a Happy New Year" is an old, old greeting but it is the very best wish your president can think of to send all Institute members as we approach that part of the year so interwoven with sacred American tradition. Indeed he would like to show his appreciation of the effective work all of you are doing for the Institute and our national defense program by sending every member a greeting card voicing the above message, supplemented by words of appreciation not only for that work, but also for the many things done to make his term of office so interesting and enjoyable. There are, however, so many of you (17,916) he must forego that desire and be content with the hope that every member will learn of his good intentions by reading this part of ELECTRICAL ENGINEERING.

Participation in Institute conventions, District, Section, and Branch meetings is a pleasant presidential duty requiring much time and travel. Your president since August 1st has attended the Pacific Coast convention, the Middle Eastern District meeting at Cincinnati; visited ten Sections and six Branches not in the Middle Eastern District; and has talked to an engineers' club, the Pacific Coast Electrical Association, and several college faculties. The ten Sections visited were: Alabama, Denver, East Tennessee, Georgia, Iowa, Louisville, Los Angeles, Muscle Shoals, San Francisco, and South Carolina. The Branches visited were those contiguous to the Sections noted. Secretary Henline and the president together visited all the places east of the Mississippi River included in the tour. At all these places the entire program was provided by your secretary and president.

Several outstanding impressions obtained from these visits are matters probably of interest for our members: The percentage of Section membership in attendance at all meetings was high; also, many of the meetings were attended by nonelectrical engineers. Attendance at the meetings frequently required many miles of travel by a rather large percentage of the membership. The Branches visited indicated that our engineering colleges have enrolled a satisfactory number of very capable young men who are being well trained to perpetuate and enrich the electrical engineering profession and continue the work of the Institute. These young men are effectively and enthusiastically conducting the work of the Branches. Indeed, the whole tour was an experience which I wish every Institute member could have, because he then would forever after be sufficiently enthusiastic about the work of the Institute to include in his activities a program of urging every electrical engineer to be a member of the AIEE.

In this connection, I am reminded of an experience a well-known engineer had when he was an engineering college senior. The president of his college gave a reception for all seniors, which several seniors, including the hero of this tale, failed to attend. Not only that, but, thinking he would not be missed, he neglected the courtesy of declining the invitation because of a previous engagement. The president, to give a lesson to all the seniors who had absented themselves from the reception without observing the formality of being excused, requested them to report at his office, where he listened to the excuses given and reprimanded them as his humor dictated. As the interview ended with the engineer about whom this statement is made, the president said: "Well, young man, you missed more than we did".

And so it is when electrical engineers engaged in the profession of electrical engineering fail to become AIEE members—the AIEE misses them but their loss is greater than that of the Institute.

We AIEE members should bear in mind that it is our duty to inform all electrical engineers, particularly the younger men, of the fact that in failing to accept the privilege of becoming members of the Institute, they are neglecting one excellent way of keeping abreast of the published advances in the profession, receiving the stimulus provided by a closer contact with men of outstanding achievement in the profession, and having the opportunity for discussing the technical papers published in ELECTRICAL ENGINEERING and the TRANSACTIONS. Indeed, as we older members survey the accomplishments and the personnel of our engineering profession, we are impressed by the fact that those responsible for electrical engineering achievements are very largely Institute members. Also, nearly all the relatively small number of successful electrical engineers who are not members of the Institute were once members for a considerable time, particularly during the period when they were advancing to high engineering and executive positions. When men who have reached high positions in industry and who let their membership lapse are discovered, we should encourage them to renew it in order that they may help the Institute give its members the benefits they obtained before they no longer felt the need of Institute membership. We also have observed that many of those who entered the engineering profession a score or more years ago and now have to their credit little professional engineering achievement are men who failed to appreciate the value of Institute membership and hence are not enrolled as members. It seems fairly logical, therefore, to conclude that Institute membership has much to do with the attainment of professional success.

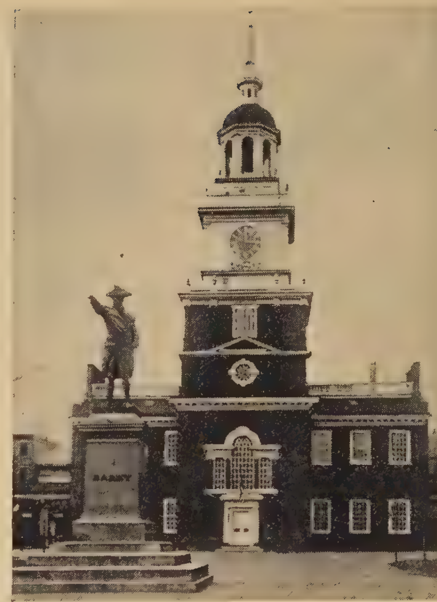
Having given this boost for the membership committee, may we discuss some other observations made on the president's initial tour of Sections.

As your secretary and president traveled from city to city, through villages and farming communities en route, we discussed with considerable pride the fact that every community appeared to be well provided with electric power lines. Furthermore, the unsettled and rural areas between cities and towns everywhere were spanned by these power lines, showing that for the most part these communities are not dependent solely upon a local or single source of power, but that cities and towns and even rural districts are interconnected thus making available everywhere under all conditions a ready and dependable power supply. Some of these electric power networks covering large areas are owned and operated by a single company. Others, while apparently unified physical networks, are made up in reality of several power systems joined by transmission lines, but each owned by independent and separate corporations, which because of the interconnections noted can sell to and buy from each other electric power according to need. Both plans appear to qualify alike in rendering reliable service to all who have need for electric power, be it the dweller of a small apartment using only a few lamps and a toaster, or an immense industry requiring thousands of kilowatts.

As these things were contemplated and we discussed our freedom to roam without question from city to city and state to state, and compared our lot with the restricted life of our friends across the seas, we were prone to become sentimental and say: Blessed is America, where men, though too much restricted in business, are still free to come and go and think and vote as they please and where co-operative efforts, such as are indicated by long power lines interconnecting power systems, may be carried on without international complications. Let us hope our situation in this respect will never change and that the present emergency conditions brought upon us by the actions of those in control of the affairs in other nations will soon be over. Let every member contemplate what engineering has done to make our standard of living what it is, and exert every effort to inform others that the true way to progress is through co-operation, which is the engineering way, rather than through narrow, nationalistic conquest, which is the emotional and unscientific way.

In the opening paragraph of this message, reference was made to the fact that Institute members are doing effective work in the national defense program. That statement was made because many engineers, particularly the younger ones, are frequently ask-

ing: "What can we do for national defense?" Our answer is: "Engineers are always developing and conducting national defense in the American way as they go about their regular daily occupations of providing things which improve our standard of living. Even in the present high-pressure and critical times only a few of us are now needed at Washington or at other special places where engineering designs are being made and engineering plans carried out. Those places for the present are well filled by some of our able and specially qualified members. Washington is provided with a list of our members and is being kept informed through the Institute office in New York about the occupation, residence, and special qualifications of our members. As need arises, the Institute will be requested to do any of the particular things needed in the defense program, some of which will be to recommend electrical engineers as needed. In the meantime, we can best serve by continuing our daily engineering occupation, whether that be research, design, manufacture, construction, operation, or study in college. Indeed, it is the hope of your president that when the time for the 1941 Christmas greeting arrives, much of the present furor will be over and the way will be clear for the free exchange of mutual greetings between all our members regardless of residence or citizenship. And may God grant that each such message will not be satire if it reads: "Peace on Earth, Good Will Toward Men."



Philadelphia Offers Historic Shrines and Variety of Industries in Convention Inspection Trips

INSPECTION trips to many nationally known industries and famous historical shrines will be an atrractive feature available to those who attend AIEE winter convention to be held in Philadelphia, Pa., January 27–31, 1941. Other features will be a technical program of some 20 sessions of diversified interest, technical conferences, the Edison Medal presentation, a dinner-dance, and the usual smoker. Details of the technical program and further information are scheduled for publication in the January issue. Headquarters for the convention will be the Bellevue-Stratford Hotel.

Philadelphia has long been known as the "Workshop of the World," and is said to produce a greater variety of manufactured articles than any other industrial center. Metropolitan Philadelphia is noted for the production of steam and hydraulic turbines, electric switchgear and instruments, radio and television sets, storage batteries, locomotives, streamlined trains, ships, iron and steel, petroleum products, publishing, cigars and cigarettes, paper products, and textiles.

Philadelphia is also rich in historical interest. Convention visitors can see Independence Hall, the Liberty Bell, Congress Hall, Carpenters' Hall, the Betsy Ross House, Old Swedes Church, and other national shrines.

ADVANCE REGISTRATION REQUIRED

Co-operation with the National Defense Commission will require advance registration for inspection trips, many of which will be restricted to American citizens. About January 1 an inspection-trip registration card will be sent with other literature from AIEE headquarters, and must be returned promptly so that arrangements with the authorities can be completed. Instructions will accompany the registration cards.

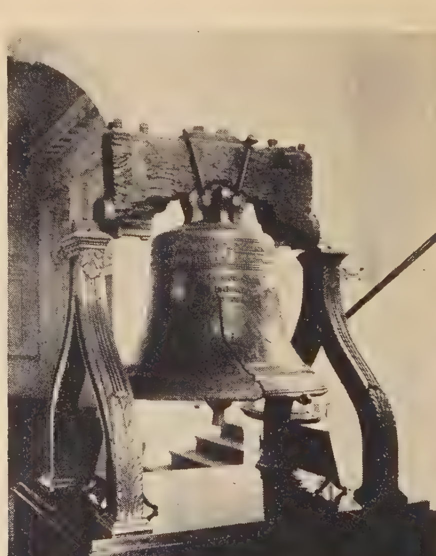
INSPECTION TRIPS

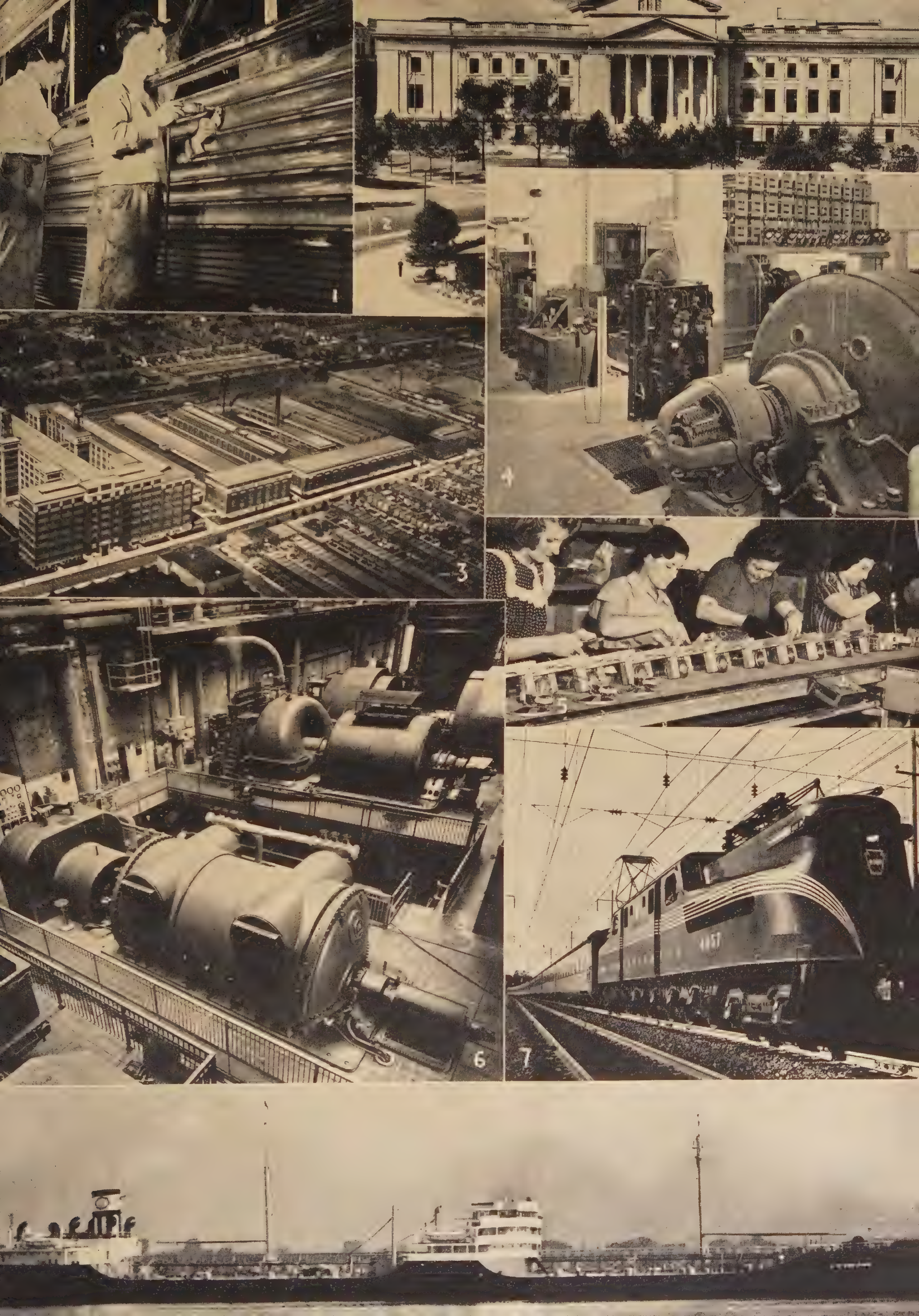
Historical and Civic Tours. These tours cover the historical, business, and residential sections of Philadelphia. Independence Hall, the Liberty Bell, the place of meeting of the first Supreme Court of the United States, the Betsy Ross House, and the spot where Benjamin Franklin flew his famous kite are among the points of interest which will be seen. Also, Fairmount Park, the University of Pennsylvania, and many other well-known landmarks will be visited.

Some Features of Winter-Convention Inspection Trips

This page: Independence Hall (above); the Liberty Bell housed in Independence Hall (lower right); the "flag room", where Betsy Ross was commissioned to make the first American flag (lower left)

Facing page: Building streamlined trains at the E. G. Budd Manufacturing Company (1); the Franklin Institute (2); air view of the Philadelphia switchgear works of the General Electric Company (3); high-power test laboratory of the I. T. E. Circuit Breaker Company (4); assembly-line production of radio receivers at the Philco Radio and Television Corporation (5); 50,000-kw topping turbine at the Schuylkill station of the Philadelphia Electric Company (6); one of the newest locomotives operating on the electrified division of the Pennsylvania Railroad (7); turbine-electric tanker of the Atlantic Refining Company (8)

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The Franklin Institute. Conceived and built as a lasting tribute to the memory of Benjamin Franklin, this unique scientific institution contains more than 4,000 action exhibits, most of which can be operated at the touch of a button. It has sections devoted to electrical engineering, aviation, chemistry, physics, transportation, and applied science. Many of the principles of electrical and mechanical equipment are demonstrated by action models which convention visitors may operate, including a full-size 265-ton locomotive valued at $100,000. In the planetarium, the sun and moon, planets and stars perform for the visitor no matter what the hour, the season, or the weather.

General Electric Company Switchgear Works. Visitors will see the latest developments in the switchgear art, products ranging from the smallest protective devices to the largest circuit breakers. The itinerary through the plant has been arranged to emphasize the results achieved by organized research co-ordinated with engineering, particularly with reference to oilless circuit breakers, high-speed protective relays operating on one cycle or less, modern testing facilities for voltages up to 3,000,000, modern safety types of vertical-lift metal-clad gear, and high-capacity station circuit-breaker equipment. At the conclusion of the shop trip, a technical demonstration and discussion of "Magne-blast" and air-blast circuit breakers will be given, supplementing the papers presented at the convention.

Westinghouse South Philadelphia Plant. Here turbines of all sizes, pumps, ejectors, high-speed forced-draft blowers, and lighting sets are built. The testing laboratory contains equipment for experimental and development purposes, particularly those problems relating to thermodynamics, aerodynamics, and hydrodynamics and for long-time tests to determine the behavior of metals when exposed to high temperatures.

Schuylkill Generating Station of Philadelphia Electric Company houses a 50,000-kw hydrogen-cooled turbogenerator (topping unit) designed for 3,600 rpm, 1,250 pounds pressure, 900 degrees Fahrenheit total temperature, and exhausting against a back pressure of 250 pounds supplied from two 600,000 pounds per hour pulverized-fuel-fired boilers. The switchhouse has recently been modernized and converted from a conventional double sectionalized bus installation to a six-section ring bus arrangement with oilless circuit breakers.

Philco Radio and Television Corporation. Here may be seen modern assembly lines for the production of radio receivers.

Pennsylvania Railroad Electrification. Opportunity will be given to inspect one of the latest electric locomotives designed for speeds in excess of 100 miles per hour and developing 8,500 horsepower; also the modern load dispatcher's office.

United States Mint is the oldest, largest, and best-equipped coinage plant in the world and the only mint open to the public. During the past year this mint produced coins for five foreign countries in addition to many millions of U. S. half dollars, quarters, dimes, nickels, and pennies. Here convention visitors will see the operation of the most highly developed modern machinery and also the largest and most valuable collection of coins and medals in the United States. All medals struck off at this mint are on display, including the Congressional Medal of Honor, medals for the Army, Navy, Marine Corps, and the medals awarded by Congress to Colonel Charles Lindbergh and Admiral Byrd. In addition, there are coins dating back to 2,000 years before the Christian era, including the "widow's mite" found near the site of the Temple of Jerusalem.

John B. Stetson Company. This factory is unique in that all the processes of hat manufacture from the raw fur-bearing skin to the finished product are carried on in this single plant. Philadelphia makes more hats than any other city in the United States.

Westinghouse Electric and Manufacturing Company plant at South Philadelphia, Pa.

Curtis Publishing Company. This plant, the home of the *Saturday Evening Post, The Ladies' Home Journal,* and *The Country Gentleman* occupies a whole city block, and millions of copies of its publications are turned out weekly. Of special interest is the new Curtis "four-and-four" precision color process by which four colors can be printed on both sides of a fast-moving sheet of paper, requiring no time interval for drying the different colors.

Burlington Generating Station of the Public Service Electric and Gas Company of New Jersey. Here may be seen the recently installed 100,000-kw cross-compound turbogenerator designed for 1,250 pounds, 950 degrees Fahrenheit total temperature. The duplicate generators for the high-pressure and low-pressure elements are both hydrogen cooled and rated 50,000 kilowatts, 3,600 rpm. Two boilers having a capacity of 550,000 pounds per hour generate steam at 1,350 pounds pressure, 950 degrees Fahrenheit total temperature, to supply this unit. The boilers are equipped to burn pulverized coal or fuel oil.

I.T.E. Circuit Breaker Company. Testing of circuit breakers using a new 32,000-kva 13,200-volt generator will be demonstrated. Visitors will also see air-blast breakers for 15,000 volts, 3,000 amperes, with interrupting capacity of 2,500,000 kva, low-voltage air circuit breakers, metal-clad switchgear for central station and industrial applications, silver-plating equipment for plating bus bars, and in the process of manufacture their line of low-voltage air breakers 15 to 50,000 amperes.

The Atlantic Refining Company Turbine Electric Tanker. An opportunity will be given to inspect one of the new tankers of the "J. W. Van Dyke" class. These tankers of 1,800 tons dead-weight are designed for an average sea speed of 13 $^1/_4$ knots and equipped with a variable speed of 4,500-kw main turbine generator and two 350-kw auxiliary turbine generator units. The main turbine is built for 600 pounds gauge steam pressure, 825 degrees Fahrenheit, and 28.5 inches vacuum. The generator is rated at 4,500 kw, 60 cycles, 2,300 volts, 3,600 rpm, and is coupled to the propeller shaft through a 500-horsepower 2,300-volt three-phase 90-rpm synchronous motor. The auxiliaries, except the feed pumps, are electrically driven. All motors except the main motor are totally encased and the switchgear and control are of the latest dead-front steel encased type.

Edward G. Budd Manufacturing Company. A pioneer in the development of steel automobile wheels and bodies, Budd also developed shot-welding for stainless steel and streamlined trains. Opportunity will be given to see the railroad car shop and automobile bodies in the making.

University of Pennsylvania. The laboratories of the Moore School of Electrical Engineering will be open for inspection. A special demonstration of the differential analyzer will be made. Opportunity will also be given to inspect the X-ray research laboratory and the atom smasher of the physics department will be demonstrated. The electrical research equipment of the Eldredge Reeves Johnson Foundation for medical physics will also be open for inspection.

The Institute Budget for the Year 1940–41

INFORMATION regarding the financial operations of the Institute is now given to the membership each year on two occasions, first with the publication of the annual report of the Institute board of directors for the fiscal year which ends April 30, and next with the adoption of a budget of income and expenditures for the appropriation year which begins October 1. The July 1940 issue of ELECTRICAL ENGINEERING, news section, pages 290–303, carries the complete report of the board of directors for the fiscal year which ended April 30, 1940, in which appears a detailed account of all activities of the organization together with financial statements for the corresponding period.

Accordingly, the budget of income and expenses for the year beginning October 1, 1940, which was adopted by the board of directors at its meeting held on October 25, is now presented in the form of a tabulation with only brief comments regarding those items which deserve special mention. For comparative purposes the tabulation includes a statement of the amounts actually received or expended during the budget year which ended September 30, 1940.

With respect to the estimate of the income to be received by the Institute during the coming year, the finance committee has again endeavored to make allowance for the probable loss of revenue from dues and from nonmember subscriptions to ELECTRICAL ENGINEERING received from abroad, which may result from conditions in those countries now affected by the war. It is estimated that the loss from these sources will be from $4,000 to $5,000 more than in the last budget year.

Upon review of the budget of appropriations it will be noted that practically all activities are being afforded financial support to the same extent as last year, and that in some cases an increased appropriation has been provided to allow for a further expansion of Institute activities.

It will also be noted that a transfer from surplus of $9,500 is to be made, to be added to the estimated receipts for the year. This is to take care of two special nonrecurring items of expense for publications. Thirty-two hundred dollars of this sum is to cover the expense of publishing in the 1940 TRANSACTIONS text matter which was presented in 1939 and therefore is more properly chargeable to the operations of that year. Sixty-three hundred dollars is to cover the effect of a change in publication policy adopted by the board last June, which will advance into the current budget year the publication of the first half of the 1941 SUPPLEMENT TO ELECTRICAL ENGINEERING—TRANSACTIONS SECTION. Under the former publication policy this expenditure would have been deferred until the 1941–42 budget year.

Increased appropriation for advance pamphlet copies is made to take care of an enlarged program of technical papers to be presented at national conventions and District meetings. The appropriation for Institute meetings provides for three national conventions and four District meetings, two more than last year.

The financial requirements for Institute Sections and Branches, for standing and technical committees, and for the various other activities shown in the tabulation have all been determined after careful study of the needs as estimated by the committees involved. The board of directors endeavors to adopt each year a budget which will make possible proper relative emphasis on the different phases of Institute activities and which limits the annual expenditures as far as possible to the amount of anticipated income for the corresponding period.

This year it is believed particularly important to have a small amount unappropriated, held for contingencies and probable additional items. The budget includes as yet no appropriation for depreciation; the appropriation for pension reserve is probably not fully adequate; it is a year in which cost levels may rise more than provided for in the budget items; and there are other matters which may call for expenditure by the Institute. Accordingly, the budget includes an "unappropriated" item of $7,910.

The success of all work planned for in the budget largely depends upon the prompt collection of membership dues, from which source over two-thirds of the total revenue of the Institute is received. It is gratifying to know that this situation is realized by the membership, as evidenced by the fact that the number of members in good standing at the beginning of the present fiscal year compares very favorably with the statistics of earlier years.

Institute Income and Expenses for Year Ending September 30, 1940, and Budget for Year Ending September 30, 1941

	Actual Income and Expenses, Year Ending 9-30-40	Budget for Year Ending 9-30-41
Income		
Dues	$205,282.38	$210,000.00
Students' fees	13,013.00	13,500.00
Entrance & transfer fees	7,880.95	8,000.00
Advertising	35,155.56	40,000.00
ELEC. ENGG.—nonmem. subscriptions	12,939.44	10,500.00
TRANS. subscriptions	7,002.70	7,000.00
Miscellaneous sales	14,973.10	16,800.00
Interest on securities	6,613.57	6,000.00
	302,860.70	311,800.00
Transfer from surplus		9,500.00
Total	$302,860.70	$321,300.00
Expenses		
Publications:		
Text matter (ELEC. ENGG. & TRANS.)	$74,126.67	$84,310.00
TRANS. SUPPLEMENT	322.88	1,425.00
Preprints	7,336.66	9,150.00
Advertising section—ELEC. ENGG.	17,230.72	20,100.00
Year Book	6,494.51	6,750.00
Miscellaneous expense	1,495.61	1,500.00
Institute meetings	12,842.60	14,200.00
Institute Sections:		
Appropriations	24,117.57	26,000.00
Other expenses	5,952.04	6,250.00
Institute Branches:		
Meetings expenses	1,180.68	1,200.00
Other expenses	2,577.99	2,850.00
Committees:		
Code of prin. prof. conduct		50.00
Edison Medal	176.86	160.00
Finance	600.00	750.00
Headquarters	61.20	100.00
Lamme Medal	181.30	210.00
Legislation		50.00
Membership	8,081.73	8,825.00
Standards	7,824.54	8,800.00
Technical committees	309.38	500.00
Traveling Expenses:		
Geo. Dist. exec. committees	2,459.40	3,000.00
Section delegates to summer conv.	6,829.73	5,900.00
Counselor delegates to summer conv.	1,145.74	1,000.00
Dist. secys. to summer conv.	927.28	800.00
District Student conferences	8,272.52	8,200.00
President's appropriation	865.50	1,500.00
Vice-presidents	855.13	1,000.00
Board of directors	6,040.02	7,250.00
National nominating committee	953.88	1,000.00
AIEE representatives		100.00
Administration:		
Headquarters' salaries	36,055.75	37,375.00
Postage	3,702.02	4,000.00
Stationery & printing	3,197.74	3,500.00
Office equipment	512.95	500.00
Trav. expense, bank charges, insurance, misc. supplies & services	4,254.68	4,500.00
Paper prizes	541.41	600.00
Joint activities:		
American Engineering Council	8,316.66	2,075.00
Amer. Co-ord. Com. Corrosion		25.00
American Standards Association	1,500.00	1,500.00
ECPD	850.00	850.00
Engg. Foundation research projects:		
Impregnated paper insulation	250.00	250.00
Insulating Oils & cable saturants	250.00	250.00
Welding	250.00	250.00
Engg. Soc. Personnel Service, Inc.	1,107.24	1,100.00
Engg. Soc. Library	9,899.90	10,075.00
Hoover Medal	175.55	....
John Fritz Medal	50.00	50.00
N.F.P.A. Dues	60.00	60.00
United Engg. Trustees building assessment	10,984.81	11,000.00
U. S. Natl. Com. I.C.I.	300.00	300.00
Miscellaneous printing, etc.		5,150.00
Authors' reprints	3,184.02	
Reprints of standards	1,576.08	
Miscellaneous	1,187.05	
Other expenses:		
Membership badges	1,804.56	1,800.00
Legal services	250.00	250.00
Pension Fund Reserve	5,000.00	5,000.00
Text paper & env. in storage	554.84	
Depreciation Reserve Fund	233.87	
Unappropriated:		
Reserved for contingencies and additional items		7,910.00
Total	$295,311.27	$321,300.00

AIEE Board of Directors Meets

The regular meeting of the AIEE board of directors was held at Institute headquarters, New York, N. Y., on October 25, 1940.

Upon request of the committee on electrochemistry and electrometallurgy, authorization was given for a joint session with the American Society of Metals during the 1941 winter convention. Also, a joint technical conference of the committee on production and application of light with the Illuminating Engineering Society during the winter convention was authorized.

The board accepted an invitation of the local Sections and Districts concerned to hold the 1941 Pacific Coast convention at Yellowstone National Park, August 27–29. A joint conference on Student activities of Districts 8 and 9 and the University of British Columbia Branch, during this convention, was authorized.

Requests for approval of dates for three previously authorized District meetings during 1941 were considered. It was the consensus of the board that the District 7 meeting in St. Louis should be held in the fall; the dates April 30 to May 2 were approved for the District 1 meeting to be held in Rochester, N. Y.; and selection of the dates for the District 5 meeting in Fort Wayne, Ind., was delegated to the president, the vice-president of District 5, and the chairman of the committee on planning and co-ordination.

It was reported that, in accordance with action of the board of directors on August 2, the executive committee, in September, notified American Engineering Council of the intention of the AIEE to withdraw from Council on December 31, 1940; and the board confirmed this action.

The board authorized the usual contribution of \$850 to the Engineers' Council for Professional Development for the year 1940–1941, and authorized a contribution of \$25 toward the expenses involved in the work of the American Co-ordinating Committee on Corrosion, in which the Institute is participating.

A resolution in memory of Past President Louis A. Ferguson, who died on August 25, 1940, was adopted (see this page).

A new Student badge, in the form of a key charm, was authorized, to be sold at a price of \$1.25.

Announcement was made that, due to the consolidation of Armor Institute of Technology and Lewis Institute, in Chicago, the Student Branches of the AIEE at these institutions had been merged into one Branch, to be known as the Illinois Institute of Technology Branch.

Upon recommendation of the standards committee, the board approved a revision of American standard for abbreviations for scientific and engineering terms—*Z*10, which had been prepared by a sectional committee of the American Standards Association.

Amendments to the rules governing the awards of national and District prizes of the Institute, recommended by the committee on award of Institute prizes, were adopted to:

1. Empower a District Executive committee to fix the dates of closure and award for the Branch paper and graduate student paper prizes in the district.

2. Provide a separate basis of grading papers for prize awards to student papers.

Authorization was given for the printing of a new edition of the pamphlet, "National and District Prizes," to include all revisions to date.

The board authorized the special committee on radio talks on electrical engineering subjects to arrange for a series of five radio talks along the lines suggested by the committee, beginning with one in connection with the 1941 winter convention and including phonograph records of the talks for use at local broadcasting stations throughout the country. The sum of \$300 was appropriated for the purpose.

A budget for the appropriation year of the Institute beginning October 1, 1940, amounting to \$321,300.00, was adopted as recommended by the finance committee.

The chairman of the committee on planning and co-ordination presented recommendations for modifications of proposals "E" and "F" of the publication committee for revisions of the publication policy of the Institute, which were adopted by the board of directors on June 27, 1940, and published in the August issue of ELECTRICAL ENGINEERING, page 332. A literal interpretation of these proposals had produced difficulties in connection with the necessary observance of budget limitations. The board approved these modifications, as an emergency action, as follows:

PROPOSAL E (placing a page limit, of six pages in type, on technical program papers to appear in the TRANSACTIONS section of ELECTRICAL ENGINEERING): In a sentence in the next to the last paragraph of the explanation of the objects of this proposal, the phrase "rather to assure publication" was changed to read "rather to give priority to publication".

PROPOSAL F: Changed to read:

PROPOSAL F: Remove in so far as practicable restrictions set by the publication budget on the number of papers which may be approved by the technical program committee.

Under this plan the publication committee and technical program committee will recommend the following to the finance committee:

a. The number of pages of advance pamphlet copies of authors' manuscripts for which provision should be made in the budget.

b. The number of pages in TRANSACTIONS for which provision should be made in the budget.

Future AIEE Meetings

Winter Convention
Philadelphia, Pa., January 27–31, 1941

Great Lakes District Meeting
Fort Wayne, Ind., April 1941

North Eastern District Meeting
Rochester, N. Y., April 30–May 2, 1941

Summer Convention
Toronto, Can., June 16–20, 1941

Pacific Coast Convention
Yellowstone National Park, August 27–29, 1941

In Memoriam

LOUIS A. FERGUSON

IN the death of Louis A. Ferguson, on August 25, 1940, at the age of 73, the Institute suffered the loss of its 21st president and one of the leading pioneers in electric power generation and distribution.

After his graduation from the Massachusetts Institute of Technology, in 1888, with the degree of bachelor of science, he was employed by the Chicago Edison Company as an engineer in the underground distribution department. He made rapid progress, serving as chief electrical engineer, 1889–1897, and in addition assuming charge of the contract department in 1893. In 1897, he was appointed general superintendent of both the Chicago Edison and the Commonwealth Electric Companies, and in 1902 he became second vice-president of both companies. The two companies were combined in 1907, and he continued as second vice-president of the Commonwealth Edison Company. He was a vice-president of that company from 1914 until his retirement on December 31, 1935.

Mr. Ferguson received national recognition for his contributions to power-system design, construction, and operation, and also for his leadership in the development of rate schedules for electric service.

He joined the Institute as an Associate in 1901, and was transferred to the grade of Member in 1904, and to the grade of Fellow in 1912. He served as manager 1904–07, vice-president 1907–08, and president 1908–1909.

RESOLVED: That the board of directors of the American Institute of Electrical Engineers hereby expresses, upon behalf of the membership, its keen regret at the death of Mr. Ferguson and its appreciation of his many contributions to the development of Institute activities, and be it further

RESOLVED: That these resolutions be entered in the minutes and transmitted to the members of Mr. Ferguson's family.

—AIEE Board of Directors, October 25, 1940

(This is expected to be a smaller amount of material than that published in advance pamphlet form.)

The technical program committee procedure would then be as follows:

1. Review and approve or disapprove all technical papers submitted for program consideration. The total number of papers that may be approved will be limited only by the advance pamphlet budget.

2. Same as previous item 2.

3. Same as previous item 3.

4. Advise the publication committee which of the papers approved by the technical program committee are recommended by the technical program committee for publication in TRANSACTIONS, the total of these not to exceed the TRANSACTIONS' budget limit. Each author is to be advised when notified of the acceptance of his paper whether or not his paper will be recommended for publication in TRANSACTIONS.

The procedure in the publication committee would not differ in any general way from the present one but the proportion of the total number of technical program committee approved papers appearing in ELECTRICAL ENGINEERING would vary, depending upon the available budget. However, with proposed changes C, D, and E above, in effect the number of such papers appearing in ELECTRICAL ENGINEERING would be increased without any increase in the publication budget. Specifically the publication committee procedure would be:

5. Publish in TRANSACTIONS all technical papers and discussions thereof which have been approved and recommended for publication by the technical program committee.

6. Previous item 5 with no change.

7. Previous item 6 with no change.

8. Previous item 7 with no change.

The following board members were selected to serve on the national nominating committee:

C. R. Beardsley, M. S. Coover, Everett S. Lee, L. R. Mapes, and H. S. Osborne

Alternates: T. F. Barton, F. Malcolm Farmer, D. C. Prince, Mark Eldredge

R. T. Henry was appointed a representative of the Institute on the Standards Council of the American Standards Association for the three-year term beginning January 1, 1941, and H. E. Farrer, H. H. Henline, and E. B. Paxton were reappointed alternates for the year 1941.

C. R. Beardsley was appointed a representative of the Institute on the board of trustees of United Engineering Trustees, Inc., for the four-year term beginning in October 1940, to fill the vacancy caused by the death of H. R. Woodrow.

Other actions by the board included the following:

Minutes of the meeting of the board of directors held on August 2, 1940, were approved.

The following actions of the executive committee as of September 16, 1940, were reported and confirmed: 17 applicants transferred and 10 elected to the grade of Member; 34 applicants elected to the grade of Associate; 17 Students enrolled.

Reports of meetings of the board of examiners held on September 12 and October 17, 1940, were presented and approved. Upon recommendation of the board of examiners, the following actions were taken: 5 applicants elected to the grade of Member; 33 applicants elected to the grade of Associate; 559 Students enrolled.

Monthly expenditures were reported by the chairman of the finance committee and approved by the board, as follows: $18,587.43 in August, $20,428.29 in September, and $30,724.24 in October.

Those present were:

President—R. W. Sorensen, Pasadena, Calif.

Past Presidents—F. Malcolm Farmer and John C. Parker, New York, N. Y.

Vice-Presidents—J. W. Barker, New York, N. Y.; J. L. Hamilton, St. Louis, Mo.; K. L. Hansen, Milwaukee, Wis.; H. W. Hitchcock, Los Angeles, Calif.; Everett S. Lee, Schenectady, N. Y.; Fred R. Maxwell, Jr., University, Ala.; C. T. Sinclair, Pittsburgh, Pa.; A. LeRoy Taylor, Salt Lake City, Utah; J. M. Thomson, Toronto, Ont.; A. L. Turner, Omaha, Nebr.

Directors—T. F. Barton, C. R. Beardsley, H. S. Osborne, New York, N. Y.; M. S. Coover, Ames, Iowa; Mark Eldredge, Washington, D. C.; R. E. Hellmund, East Pittsburgh, Pa.; F. H. Lane, L. R. Mapes, Chicago, Ill.; D. C. Prince, Schenectady, N. Y.; R. G. Warner, New Haven, Conn.

National Treasurer—W. I. Slichter and *National Secretary*—H. H. Henline, New York, N. Y.

AIEE Prize Rules Changed for National and District Papers

Provision in the Institute's 1940–41 budget has been made for cash awards to accompany the national and District prizes for initial and Branch papers to be awarded during the current year, as indicated below.

All technical papers presented before the Institute are eligible under the AIEE paper prize regulations for competitive consideration for one or more of the established prizes, regardless of whether presented before a Branch meeting, a Section meeting, a District meeting, or a national convention, the several classes of prizes providing for equitable competition.

National prizes that may be awarded annually, and those to be accompanied by cash awards during the current year, are as follows:

1. Best paper prizes (certificates):
   - *Engineering practice*
   - *Theory and research*
   - *Public relations and education*
2. Prize for initial paper ($100 and certificate)
3. Prize for Branch paper ($100 and certificate)

District prizes that may be awarded annually in each of the geographical Districts of the Institute, together with the cash awards provided for the current year, are:

1. Prize for best paper (certificate)
2. Prize for initial paper ($25 and certificate)
3. Prize for Branch paper ($25 and certificate)
4. Prize for graduate student paper (certificate)

PERIODS OF COMPETITIONS

The national "best paper prizes" and the national "initial paper prize" are awarded for papers presented during the calendar year, except best paper prize in the class of public relations and education. In this class the award is for a paper presented subsequent to those considered at the time of the last previous award in this field and prior to the end of the calendar year. For the national "prize for Branch paper" only papers presented during the preceding academic (college) year, July 1 to June 30, inclusive, will be considered.

The District "prize for best paper" and the District "prize for initial paper" are awarded only for papers presented subsequent to the period covered by the last previous award in the class and prior to the end of the last calendar year. The District "prize for Branch paper" and the District "prize for graduate student paper" are awarded only for papers presented subsequent to the period covered by the last previous award in the class and prior to the end of the last academic (college) year, July 1 to June 30, inclusive.

TIME OF AWARDS

All of the national prizes and the District "prize for best paper" as well as the District "prize for initial paper" shall be awarded prior to May 1 of the succeeding year. The District "prize for Branch paper" and the District "prize for graduate student paper" will be awarded as determined by the District executive committee and announced to all Branches in the District.

HOW TO SUBMIT PAPERS

For the national prizes all papers approved by the technical program committee which were presented at the national conventions or District meetings will be considered for the best paper prizes and the initial paper prize without being formally offered for competition. All other papers which were presented at Section or Branch meetings must be submitted in triplicate with written communications to the national secretary on or before February 15 of the following year, stating when and where the papers were presented.

For the District "prize for best paper" and the District "prize for initial paper" papers shall be submitted at least in duplicate by authors or by officers of the Section, Branch, or District concerned to the District secretary on or before February 15. The District secretary will refer the papers either to the District executive committee or a committee appointed by the District executive committee authorized to make the awards. For the District "prize for Branch paper" and "prize for graduate student paper" papers shall be submitted at least in

A Good Deed

Mr. Institute Member:

A Boy Scout is expected to do one good deed each day, but we only ask you as an Institute member to do one good deed each year, viz., to suggest to your Section membership committee the name or names of men of your acquaintance who are eligible for membership but are not now affiliated with the Institute.

Or better still, if you wish to make it a real good deed, in addition to sending in their names, talk with them yourself and get them interested. This will pave the way for the membership committee contacts and improve the possibilities of their success.

O. C. Brill

Chairman, National Membership Committee

duplicate by authors or by officers of the Section, Branch, or District concerned to the District secretary in accordance with dates of closure and of award, as fixed by the District executive committee and announced to all Branches in the respective Districts.

The basis of evaluating all student papers has been changed to bring it more in conformity with the objectives of such papers. Those wishing further information may obtain a booklet entitled "National and District Prizes" from AIEE headquarters, 33 West 39th Street, New York, N. Y.

District

District 1 Executive Committee Meets at Pittsfield

With an attendance of Section and other representatives as noted in the following list, the executive committee of the Institute's North Eastern District met at Pittsfield, Mass., Friday, October 4, 1940:

R. G. Lorraine, secretary, North Eastern District
H. H. Henline, national secretary, AIEE
A. G. Conrad, secretary, Connecticut Section
G. L. Dawes, past vice-president
E. M. Hunter, chairman, Schenectady Section
T. T. Woodson, secretary, Schenectady Section
A. H. Magnusan, chairman, Worcester Section
V. Siegfried, national membership committee
Eric A. Walker, Student Branch counselor, Connecticut
W. I. Middleton, secretary-treasurer, Boston Section
O. E. Sawyer, secretary-treasurer, Providence Section
H. A. Baines, chairman, Providence Section
E. V. Deblieux, chairman, Pittsfield Section
W. K. Parks, secretary, Niagara Frontier Section
H. D. Griffith, chairman, Springfield Section
Isaiah Creaser, secretary, Springfield Section
W. F. Cotter, chairman, Rochester Section
H. H. Race, chairman, Schenectady Section
M. E. Scoville, secretary-treasurer, Pittsfield Section
M. G. Northrop, chairman, Ithaca Section
R. W. Adams, chairman, Boston Section
E. S. Lee, vice-president, AIEE

Actions taken by the committee include the following:

1. Approved the dual method of transferring to Fellow grade, as discussed at the annual conference of officers, delegates, and members held in connection with the 1940 summer convention at Swampscott, Mass., and reported on pages 335–6 of the August issue of ELECTRICAL ENGINEERING.
2. Approved Vice-President E. S. Lee's appointment of the following men to serve with him on the District co-ordinating committee: R. D. Lorraine of Schenectady, A. G. Conrad of New Haven, H. D. Griffith of Springfield, O. E. Sawyer of Providence, M. G. Northrop of Ithaca, and E. A. Gruppe of Syracuse.
3. Approved Vice-President Lee's appointment of W. F. Cotter of Rochester and C. E. Tuites of Rochester to serve with the members of the District co-ordinating committee as the general committee for the District meeting scheduled to be held in Rochester April 30–May 2, 1941.
4. Approved Vice-President Lee's appointment of D. S. Snell of Schenectady, W. I. Middleton of Cambridge, and W. K. Parks of Buffalo to act as judges for the District's initial and best-paper prize awards, and W. W. Cotner of Ithaca, R. C. Porter of Boston, and A. G. Conrad of New Haven to act as judges for Student Branch paper prize awards.
5. Voted financial support to the extent of some \$200 for District student convention activities, and \$30.00 for District prizes.
6. Adopted an assessment of \$20.00 plus five cents per AIEE member for each Section in the North Eastern District, to defray the expenses of general District activities.
7. Elected Past-Vice-President C. L. Dawes to represent the North Eastern District on the national nominating committee.

Chairman E. A. Walker of the District's committee on student activities reported that the District's 17 student branches had a total membership of nearly 400 Enrolled Students, with a gross total attendance of 6,500 during the past school year at 141 branch meetings for which the programs included some 70 student talks; that there was a total attendance of about 150 at the Student District conference held at Rensselaer last Spring where 5 graduate and 16 undergraduate student papers were presented. Student branch counselors are planning to hold this year's student convention in connection with the District meeting scheduled for Rochester. AIEE national affairs of interest to the District and its Sections were discussed by Past-Chairman H. H. Race of the national sections committee, Vice-Chairman Victor Siegfried of the national membership committee, and National Secretary H. H. Henline.

District 2 Co-ordinating Committee

By action of the District 2 executive committee at its meeting held October 10, 1940, during the Middle Eastern District meeting at Cincinnati, Ohio, the following men were selected to serve as the co-ordinating committee for the Middle Eastern District in connection with the 1942 District meeting in Pittsburgh, Pa.:

F. S. Fiske, Maryland Section
W. R. Hough, Cleveland Section
M. B. Wyman, Pittsburgh Section
W. J. D. Geary, Lehigh Valley Section

Executive Committee of District 6 Meets at Denver

The executive committee of the North Central District held its annual meeting at the University Club, Denver, Colo., November 1, 1940, with the following Section and other representatives present:

A. L. Turner, vice-president
Nelson R. Love, vice-chairman, national membership committee
W. G. Rubel, chairman, Denver Section
John R. Walker, secretary, Denver Section
L. A. Bingham, chairman, Nebraska Section
John M. Gibb, secretary, Nebraska Section
H. F. Rice, chairman, District committee on student activities
I. M. Ellestad, District secretary

Actions taken by the executive committee included the following:

1. Nominated Arthur L. Jones (F'38) vice-president and district manager of the General Electric Company at Denver, for the office of AIEE vice-president from District 6 for the two-year term beginning August 1, 1941. Mr. Jones is past chairman of the Denver Section, 1927–28.
2. Appointed Albert S. Anderson past chairman of the Denver Section (1938–39) to represent District 6 at the forthcoming January meeting of the national nominating committee. Byron E. Cohn of Denver was selected as District alternate representative.
3. Took action recommending that each Section in District 6 consider making an appropriation of about \$7.50 to provide a fund to be used for District prizes for student papers, awards to be made at the annual conference on student activities.
4. Appointed Chairman W. G. Rubel and Secretary J. R. Walker of the Denver Section and District Vice-Chairman Nelson R. Love of the national membership committee to constitute a committee of judges to consider the student papers that will be presented at the annual conference on student activities to be held at the University of Denver April 18–19, 1941.
5. Endorsed the invitation from the Denver Section to the Institute to hold the 1942 annual summer convention in Denver.

Other items of District business discussed included the matter of membership and the subject of rules governing the awards of District prizes for Student Branch papers.

Section

Milwaukee Section Forms Discussion Groups

Three technical discussion groups have been organized by the AIEE Milwaukee Section, with the objectives of providing forms for technical discussion and giving young engineers experience in presenting papers. The groups were formed after replies to a questionnaire showed great interest in the plan. Others will be added if sufficient demand appears.

The co-ordinating chairman of the project is C. J. Fechheimer and the three groups, which held their first meetings in November, are:

Group A, electrical machinery—S. H. Mortensen, chairman

Group B, power applications and controls—K. L. Hansen, chairman

Group C, electronics—Walter Richter, chairman

Each group expects to meet about four times a year. Only AIEE members or local members of the Section may participate, but any member may join more than one group.

Abstracts

TECHNICAL PAPERS are previewed in this section as they become available in advance pamphlet form. Copies may be obtained by mail by remitting price indicated to the AIEE order department, 33 West 39th Street, New York, N. Y.; or at five cents less per copy if purchased at AIEE headquarters or at AIEE convention or District-meeting registration desks.

The papers previewed in this issue will be presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941.

Basic Sciences

41-4—Calculation of Initial Breakdown Voltages in Air; *D. W. Ver Planck (A'31). 20 cents by mail.* Although spark-over and corona starting voltages can be predetermined satisfactorily in cases for which empirical formulas or curves are available, a more generally applicable method is needed. An approach to such a method is through a modification of Townsend's theory, which, though possibly lacking in rigor, suffices in many cases for the accurate calculation of breakdown voltages. The present paper outlines the theory and shows that the initial breakdown voltage may be calculated using two quantities characteristic of the gas for cases where the field, if nonuniform, converges toward the cathode. Formulas ex-

pressing one of the characteristic quantities for air, the Townsend coefficient α, are assembled, and a formula for the second quantity is deduced from an analysis of published spark-over gradients for plane gaps. The method is applied to two cases and the results are shown to be in agreement with experiment.

41-6—A Five-Figure Table of the Bessel Function $I_n(x)$; *H. B. Dwight (F'26). 15 cents by mail.* The modified Bessel function of the first kind, $I_n(x)$, where x is a real quantity, is of widespread application, but it is of particular interest to electrical engineers, since the current and voltage for a traveling wave on an electric line can be expressed as a series of these functions. A table of these functions was published in the Report of the British Association for the Advancement of Science, 1889, and has been reprinted in "Bessel Functions" by Gray, Mathews, and MacRobert. While a large number of significant figures were given, the arguments were 0.2, 0.4, 0.6, etc. The interpolation, as used in engineering work, is somewhat easier and more according to a decimal system when arguments 0.1, 0.2, 0.3, etc., are used. Accordingly, additional values for a five-figure table have been computed, and the enlarged five-figure table is given in this paper.

41-9—D-C Breakdown Strength of Air and of Freon in a Uniform Field at High Pressures; *J. G. Trump (A'31), F. J. Safford (A'35), and R. W. Cloud (A'39). 15 cents by mail.* This paper extends d-c breakdown studies in air and in Freon 12 (dichlorodifluoromethane) at high pressures and in a uniform field to higher voltages than have been reported previously, and indicates reasons for the observed departures from Paschen's law and for the relatively high insulating strength of the Freon. D-c breakdown studies of air in a uniform field have been extended to 1,000 kv. D-c studies of Freon (CCl_2F_2) have been extended to over 350 kv and to 135 pounds per square inch absolute. The mechanisms which account for the higher insulating strength of such gaseous compounds as CCl_2F_2 are outlined and their possibilities and limitations in the insulation of high-voltage apparatus are briefly discussed.

Communication

41-8—Hollow Pipes of Relatively Small Dimensions; *W. L. Barrow (M'33), H. Schaevitz (A'40). 15 cents by mail.* The hollow-pipe type of conductor for ultra-high-frequency electromagnetic energy, although possessing several desirable features, has the disadvantage that its transverse dimensions are relatively large; namely, of magnitude comparable to the wave length. The object of this paper is to lessen this encumbrance by describing pipes that have transverse dimensions several times smaller than those of the simple forms previously proposed. Several cross-sectional shapes for hollow-pipe transmission lines are described that provide lower operating frequencies for given outside dimensions than do the simple shapes heretofore proposed. The theory for one such line, the "separate coaxial cable", is derived, and experiments are reported. Cavity resonators embodying these principles are also described.

Electrical Machinery

41-1—"Rotor-Bar Currents in Squirrel-Cage Induction Motors"; *J. S. Gault (M'30). 20 cents by mail.* The rotor of a squirrel-cage induction motor is an extremely simple and rugged piece of mechanism; and due largely to this simplicity, it resists accurate analysis of its behavior by ordinary testing technique. Its design has been perfected by cut-and-try methods, making assumptions with respect to rotor current to simplify the theory, but the actual current in the bars has remained a mystery. The purposes of this paper are: first, to present oscillograms of rotor-bar currents; second, to extend the theory of induction motors to include the computation of rotor-bar currents; and third, to show the effect of the rotor-current harmonics upon the efficiency of the motor.

41-2—Analysis of Short-Circuit Oscillograms; *W. W. Kuyper (A'34). 15 cents by mail.* The analysis of short-circuit oscillograms to obtain synchronous-machine reactances is usually made by means of the equations developed from symmetrical-component theories. These equations have been employed by previous writers on the subject and have been incorporated in published standards. Because symmetrical-component methods usually start from the assumption of sinusoidal currents of single frequency in the armature, and because it is known that short-circuit currents depart appreciably from the simple sinusoidal form, it is desirable to know the effect of removing the assumption of sinusoidal currents on the equations used in the analysis of short-circuit oscillograms. Methods of analyzing the oscillograms of short-circuit currents of synchronous machines, in accordance with the two-reaction theory, are presented in this paper. Differences between the results found here and the more generally accepted equations, based on symmetrical components, are pointed out.

Power Transmission and Distribution

41-5—Impulse and 60-Cycle Characteristics of Driven Grounds; *P. L. Bellaschi (F'40). 20 cents by mail.* Driven grounds are important in electric power transmission and distribution. In fact, they comprise one of the essential elements in the art of lightning protection. Yet, to this day, the value of protection derived from grounds under actual operating conditions of lightning discharge is difficult to state in full quantitative measure. And the reason for this situation lies partly in the lack of fundamental knowledge of the impulse characteristics of driven grounds. In part, the difficulty also is due to the complex factors that inherently make up driven grounds and ground systems. This paper presents an investigation supplying test data on the impulse and 60-cycle characteristics of common rods driven in natural soil (largely clay composition). It sums up and analyzes the results in the characteristic curve of the ratio of impulse to 60-cycle resistance for impulse currents that represent conditions ranging from a traveling surge to direct strokes of lightning. The basic reasons for the performance of grounds under impulse currents are pointed out in so far as the experimental data and observations permit. From this investigation the desirability of establishing the characteristic for other typical soils and for other common types of grounds (electrodes) is apparent.

Instruments and Measurements

41-3—Automatic Printing Ammeter; *T. G. LeClair (F'40). 20 cents by mail.* A new meter has been developed which will automatically read and record in numerals, at predetermined time intervals, the ampere loading on 50 different electric circuits. This meter also adds meter readings on groups of circuits and prints these totals in columns beside the meter readings. The paper outlines briefly the reasons for developing such a device. The paper also describes, with the aid of schematic diagrams, the process by which the meter obtains and prints all the meter readings on a single "log sheet". The following are incidental benefits derived from the use of the meter: greater accuracy, greater legibility, duplicate records, and uniform timing of readings.

Personal • • •

E. E. Minor, Jr. (A'35) research and development engineer, the Glenn L. Martin Company, Baltimore, Md., has been appointed chairman of the Institute's newly formed committee on air transportation. He was born at Baltimore February 18, 1907, and received the degrees of bachelor of engineering, 1930, and doctor of engineering, 1934, from Johns Hopkins University. During part of 1934 he was employed by the Pennsylvania Railroad at Washington, D. C., as assistant electrical engineer on high-voltage cable installation. While doing graduate work at Johns Hopkins, he was engaged in research on space charge effects in liquid dielectrics, continuing that work until 1935. Following a year and a half of work on job analysis in the United States Department of Labor, he became staff electrical engineer for the Glenn L. Martin Company, later becoming electrical engineer and research and development engineer. During this period he has been responsible

E. E. MINOR, JR.

for the progress and development of electrical engineering as applied to large aircraft. He has also carried on consulting work in electrical engineering. He is also a member of Sigma Xi and of the Institute of Aeronautical Sciences.

O. P. Cleaver (A'36) lighting engineer, Westinghouse Lamp Division, Bloomfield, N. J., and **F. A. Hansen** (M'31) managing director, Western Institute of Light and Vision, Los Angeles, Calif., have been elected regional vice-presidents of the Illuminating Engineering Society for 1940–41, in accordance with the society's recent establishment of eight geographical divisions, called "regions." Mr. Cleaver, who will serve as vice-president of region B, comprising the New York and New England sections of the IES, was born January 8, 1907, at Rowlettes, Ky., and received the degrees of bachelor of science in electrical engineering from Georgia Institute of Technology in 1928 and master of science in electrical engineering from Yale University in 1930. Since 1930 he has been with the Westinghouse Lamp Division; from 1930 to 1935 as district engineer at Chicago, Ill. Since 1935 he has been in charge of the illumination section, commercial engineering department. He is a member of the Institute's committee on production and application of light. Mr. Hansen will serve as vice-president of region "H," covering the Pacific Coast area. He was born December 29, 1898, at Mineral, Idaho, and studied electrical engineering at the Bliss Electrical School. For some years he was Pacific Coast representative of the Hollophane Company, Inc., and since 1935 has been managing director of the Western Institute of Light and Vision. Both men have been active in committee and section work in the IES.

L. R. Ludwig (A'28) formerly manager of the protective devices engineering, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been made manager of the two newly combined divisions of circuit breaker and protective devices engineering. A native (1904) of Kansas City, Mo., he received the degree of bachelor of science in electrical engineering from the University of Illinois in 1925, and entered the student course at Westinghouse the same year. He has been with the company continuously except for the year 1929–30, which he spent in graduate study at the University of Berlin as recipient of the first Lamme Memorial scholarship. In 1931 he entered the research division of railroad motor engineering, and since 1935 has been in the switchgear division. He was coauthor of the AIEE national prize best paper in theory and research in 1933, and received honorable mention in the same award in 1936.

R. D. Bennett (F'35) professor of electrical measurements, Massachusetts Institute of Technology, Cambridge, has been appointed lieutenant-commander in the United States Naval Reserve, with headquarters at the Naval Ordnance Laboratory, Washington, D. C. Born June 30, 1900, at Williamson, N. Y., he received the degrees of bachelor of science (1921) and master of science (1923) in electrical engineering from Union College, and that of doctor of philosophy from the University of Chicago in 1925. He taught in mathematics (1921–23) and physics (1925–26) at Union College, Schenectady, N. Y., and was National Research fellow in physics at Princeton University, Princeton, N. J., 1926–27, and at California Institute of Technology, 1927–28; and research associate at the University of Chicago, Chicago, Ill., 1928–31. He went to MIT as associate professor of electrical measurements in 1931, later becoming professor.

F. E. Terman (A'23, M'34) executive head, electrical engineering department, Stanford University, Stanford University, Calif., has been elected president of the Institute of Radio Engineers for the year 1941. He is at present a vice-president of the society. Born June 10, 1900 at English, Ind., he received the degrees of bachelor of arts (1920) and electrical engineer (1922) from Stanford University and that of doctor of science from Massachusetts Institute of Technology in 1924. He entered the electrical engineering department at Stanford University in 1925, becoming assistant professor in 1927, associate professor in 1930, and later professor. He is the author of books and articles on communications, holds a number of patents, and has also carried on consulting work.

E. O. Shreve (A'06) vice-president in charge of apparatus sales, General Electric Company, Schenectady, N. Y., has been elected president of the National Electrical Manufacturers' Association for 1940–41. A native (1881) of Mapleton, Iowa, he received the degree of bachelor of science in electrical engineering in 1904. He went with General Electric as a student engineer the same year and has been with the company ever since. He was sent to the Pacific Coast in 1906 as supply salesman, and in 1917 became manager of the San Francisco office. He was made manager of the industrial department at Schenectady in 1926, assistant vice-president in 1929, and vice-president in 1934.

H. B. Burr (A'21, M'40) has retired as plant engineer, Wisconsin Telephone Company, Milwaukee. Born July 26, 1875, at Milwaukee, he studied engineering at the University of California. Before entering the employ of the Wisconsin Telephone Company in 1905, he was employed as a draftsman by the Milwaukee Engineering Company, the Bucyrus Manufacturing Company, and the Kearney and Trecker Company, all of Milwaukee, and from 1903 to 1905 as assistant to superintendent of construction, Allis-Chalmers Company, Milwaukee. He went with the Wisconsin Telephone Company as inspector, became assistant aerial construction engineer in 1907, and in 1921 was made plant engineer.

L. B. Bender (A'20, M'27) has joined the Westinghouse Electric and Manufacturing Company as engineer for the research products department, with headquarters at Baltimore, Md., having retired at his own request as colonel in the Signal Corps, United States Army. He has been a commissioned officer in the Army since 1909, and has been closely identified with research work in the Signal Corps, as he has served as director of each of the Signal Corps laboratories, and as chief of the research and development division of the Chief Signal Officer's office in Washington, D. C.

F. E. Bell (M'35) has been appointed construction engineer for the new steam generating plant which is being built by the Tennessee Valley Authority near Watts Bar Dam, Tenn. He has been associated with TVA since 1934, serving as assistant construction engineer of the Joe Wheeler and Gunthersville Dams in Alabama. Previously he had been with United Engineer and Constructors, Inc., Philadelphia, Pa.; United Gas Improvement Contracting Company, Philadelphia; and Stone and Webster, Inc., Boston, Mass.

E. C. Stone (M'19, F'31) vice-president and general manager, Duquesne Light Company, Pittsburgh, Pa., has been elected president of the Pennsylvania Electric Association for 1940–41. **H. M. Rankin** (A'20, M'22) superintendent of power supply, Metropolitan Edison Company, Reading, Pa., was elected a member of the executive committee of the Association, and **H. S. Fitch** (A'18) general superintendent of substations, West Penn Power Company, Pittsburgh, Pa., was elected vice-chairman of the Association's engineering section.

A. D. Hinckley (A'27, M'38) assistant to the dean of the faculty of engineering and instructor in electrical engineering at Columbia University, New York, has been granted a temporary leave of absence to serve as senior consultant in engineering education in the Office of Education of the Department of the Interior, Washington, D. C.

K. A. Hawley (A'09, F'35) formerly chief engineer, Victor Insulators, Inc., Victor, N. Y., has been appointed engineer of new products, Electric Power Equipment Corporation, Philadelphia, Pa. He had been with Victor Insulators since 1935, and previously was chief engineer of the Locke Insulator Corporation, Baltimore, Md.

W. V. Kahler (M'39) chief engineer, Illinois Bell Telephone Company, Chicago, Ill., has been given leave of absence to report to W. H. Harrison (A'20, F'31) vice-president and chief engineer of the American Telephone and Telegraph Company, now with the National Defense Advisory Commission, Washington, D. C.

E. E. Wyland (A'29, M'39) formerly general plant supervisor, Mountain States Telephone and Telegraph Company, Denver, Colo., has been appointed Colorado plant superintendent. He has been with the company since 1924 and was appointed general plant supervisor in 1939.

A. M. Musgrove (A'30, M'37) formerly assistant engineer, transmission and distribution, Public Service Electric and Gas Company, Newark, N. J., has been assigned to active duty with the United States Army as engineer officer for the Third Military Area, with headquarters at Newark.

D. J. LaMothe (A'35) has been appointed an instructor in electrical engineering at Michigan College of Mining and Technology, Houghton. A graduate of that institution (1934) he has been engaged in research at the American Television Institute, Chicago, Ill.

W. M. Hanna (A'26) formerly employed in the engineering division, central station department, General Electric Company, Schenectady, N. Y., is now assistant to the electrical engineer, Consolidated Gas, Electric Light, and Power Company, Baltimore, Md.

E. A. Walker (A'34) formerly chairman of the department of electrical engineering, Tufts College, Medford, Mass., has been appointed associate professor of electrical engineering at the University of Connecticut, Storrs.

F. J. Amador (A'36) formerly assistant professor of electrical engineering, New Mexico State College, State College, is now an assistant engineer for the United States Government at the Panama Canal, engaged on the design of the third set of locks.

G. E. Hulse (M'22) chief engineer, The Safety Car Heating and Lighting Company, New Haven, Conn., has been elected a manager of The American Society of Mechanical Engineers to serve on the council of that society for a three-year term.

J. A. Caparo (M'18, F'32) professor of electrical engineering, University of Notre Dame, Notre Dame, Ind., has received the Notre Dame Alumni Association award, granted annually to a member of the faculty in recognition of outstanding work.

R. W. Wilbraham (M'21) chief electrical engineer, United Engineers and Constructors, Inc., Philadelphia, Pa., has been appointed chairman of the committee on electrical equipment of the Edison Electric Institute for the year 1940–41.

S. P. MacFadden (A'19, M'30) has been elected to serve the Northwest Electric Light and Power Association as vice-president for 1940–41. He is vice-president in charge of operations for Puget Sound Power and Light Company, Seattle, Wash.

O. A. Becklund (A'38) formerly instructor in electrical engineering, Case School of Applied Science, Cleveland, Ohio, is now a member of the department of electrical engineering at the University of Minnesota, Minneapolis.

L. D. Colvin (A'39) has been granted a year's leave of absence from his position as junior engineer, Pacific Gas and Electric Company, San Francisco, Calif., to serve as first lieutenant in the Signal Corps, United States Army, stationed at San Francisco.

L. P. Winsor (A'40) formerly assistant at the Graduate School of Engineering, Harvard University, Cambridge, Mass., has now joined the staff of the Case School of Applied Science, Cleveland, Ohio.

Meirion Davies (A'37) managing director, Langley Manufacturing Company, Vancouver, B. C., Canada, has been elected chairman of the Granville Island branch of the Canadian Manufacturers' Association.

J. O. Binney (M'35) formerly electrical engineer, Metropolitan Water District of Southern California, Los Angeles, is now employed in the chief engineer's office of the Southern California Edison Company, Los Angeles.

S. E. Gates (A'36) manager, Los Angeles (Calif.) office, General Electric Company, has been elected a vice-president of the Pacific Coast Electrical Association for the coming year.

R. P. Long (A'34) formerly general plant employment supervisor, eastern district, Bell Telephone Company of Pennsylvania, Philadelphia, has been appointed general plant manager.

R. W. King (M'35) assistant to the president, Bell Telephone Laboratories, has been transferred to the position of assistant vice-president, American Telephone and Telegraph Company.

C. A. Collier (M'23) vice-president in charge of sales, Georgia Power Company, Atlanta, Ga., has been appointed Georgia representative on the southern industrial mobilization committee for national defense.

J. H. Herron (M'35) president, the James H. Herron Company, Cleveland, Ohio, has been made an honorary member of the Cleveland Engineering Society.

L. S. White (A'25) formerly district manager, Portland General Electric Company, Gresham, Ore., has been transferred to the Portland office of the company.

Obituary • • •

Charles Hesterman Merz (A'95, M'10, F'13) consulting electrical engineer, senior partner, Merz and McLellan, London, England, died during October 1940 when his London home was destroyed by a bomb. He was born at Gateshead-on-Tyne, England, October 5, 1874, and received his technical education at Armstrong College, Newcastle-on-Tyne, as a student of the University of Durham. He was awarded the honorary degree of doctor of science by the University of Durham in 1932. He was an apprentice of the Newcastle-on-Tyne Electric Supply Company; pupil engineer for Robey and Company, Lincoln; and resident engineer for Croydon Corporation Electricity Works (1897) and for Cork Electric Tramways and Lighting Company, Ltd. (1898–99) before devoting himself to consulting practice. He was especially concerned with power supply and designed and carried out electric power and traction work in England, India, Australia, Africa, the United States, and South America. He was a member of the Home Office committee on electricity in mines, 1910; chairman, electric power supply subcommittee of the coal conservation committee of the Ministry of Reconstruction, 1917; member of the Board of Trade committee on electric power supply, 1917; and director of experiments and research for the British Admiralty, 1918. He received the Faraday Medal of the Institution of Electrical Engineers of Great Britain in 1931, and was a past vice-president of that organization. He also was a member of the Institution of Civil Engineers, Great Britain, of the British Engineering Standards Committee, the Electrochemical Society (American), and the Franklin Institute.

John Renshaw Carson (A'19, F'33) research mathematician, Bell Telephone Laboratories, New York, N. Y., died October 31, 1940. He was born June 28, 1886, at Pittsburgh, Pa., and received the degrees of bachelor of science, 1907, electrical engineer, 1909, master of science, 1912, from Princeton University, and the honorary degree of doctor of science from Brooklyn Polytechnic Institute 1936. From 1907 to 1910 he was a student engineer with the General Electric Company, Schenectady, N. Y. He was employed in the research division of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., 1911–12, and as an instructor in physics and electrical engineering at Princeton University, Princeton, N. J., 1912–14. In 1914 he entered the engineering department of the American Telephone and Telegraph Company, New York, N. Y., and in 1917 was transferred to the department of development and research as engineer of transmission theory development. When that department was consolidated with the Bell Telephone Laboratories in 1934, he assumed the position of research mathematician in that organization. He received the Liebmann Memorial Prize of the Institute of Radio Engineers in 1924, and the Elliott Cresson Medal of the Franklin Institute in 1939, and was named a "modern pioneer" by the National Association of Manufacturers in 1940. He was also a member of the Institute of Radio Engineers, the American Mathematical Society, and Phi Beta Kappa. He was the author of books and technical papers and held a number of patents.

Eli Franklin Bush (A'08) attorney at law, Los Angeles, Calif., died September 6, 1940. He was born at Quaker, Mich., April 6, 1883, received the degree of bachelor of science from the University of Michigan in 1906, and also studied law at the University of Southern California. He entered the employ of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., in 1906, and the following year was transferred to the company's sales office at Philadelphia, Pa., as understudy salesman. From 1908 to 1915 he was salesman for the Philadelphia office, and for the next two years worked on application of motors to machine tools and various kinds of machinery. In 1917 he was put in charge of that work at East Pittsburgh. He went with the United States Bureau of Aircraft Production, procurement division, the following year, and later went to Los Angeles, Calif., where he studied law and was admitted to the bar in 1923. Since that time he had been engaged in general law practice in Los Angeles.

William Norman McAnge, Jr. (A'25, M'28) president and treasurer, Inter-Mountain Telephone Company, Bristol, Tenn., died August 30, 1940. He was born at Suffolk, Va., August 1, 1882, and received the degree of bachelor of science from Virginia Polytechnic Institute in 1902. He was chief

engineer of the Atlantic Coast Construction Company, Suffolk, Va., 1902–06; sales engineer, Electric Heating Manufacturing Company, Los Angeles, Calif., 1906–07; manager, Consolidated Telephone Company, Pittston, Pa., 1907. In 1908 he became manager of the Jackson (Tenn.) Home Telephone Company, and in 1910 became general manager of the Allen Telephone Properties, which were operating telephone companies in Mississippi, Alabama, and Tennessee. He was later made vice-president and then president of that group of companies. In 1925 he assumed the positions with the Inter-Mountain Telephone Company which he held until his death.

Harris A. Robbins (A'08, M'13) superintendent of power, Brooklyn-Manhattan Transit Corporation, Brooklyn, N. Y., died October 25, 1940. He was born at Southport, N. Y., August 9, 1879, and received the degree of bachelor of science in electrical engineering from Pennsylvania State College im 1901. He was employed by the Brooklyn Rapid Transit Company in 1901 and spent his entire career with that company and its successor, the Brooklyn-Manhattan Transit Corporation. He became assistant erecting engineer in 1903, assistant engineer on electrical design in 1905, and in 1907 was placed in charge of electrical design and construction of power station and substations. Since 1909 he had held the position of superintendent of power. He was also a member of The American Society of Mechanical Engineers and the American Electric Railway Association.

Albert Gail Fuller (A'37) electrician, Phelps Dodge Corporation, Ajo, Ariz., died March 11, 1940, according to information just received. He was born at Los Angeles, Calif., December 21, 1903, and had been engaged in electrical work since 1924. During 1926–27 he was foreman of hydroelectric powerplant number 2 of the City of Los Angeles, Calif. He later was engaged on power house construction for the Southern California Edison Company, Ltd., at Long Beach, Calif.; was in charge of maintenance of electrical equipment for the Mutual Cotton and Oil Company, Phoenix, Ariz.; was employed on construction of powerhouse electrical equipment for the Calumet and Arizona Mining Company. From 1931 to 1934 he engaged in electrical contracting in Los Angeles, and since 1934 had been employed by the Phelps Dodge Corporation.

Joseph Hegy (A'38) San Jose, Calif., died November 5, 1938, according to information just received. He was born at Minneapolis, Minn., June 14, 1907. He received the degree of bachelor of arts in 1935 from Stanford University, and later carried on graduate work in electrical engineering at that institution.

Correction

William G. Quirk (A'16, M'27) engineer, division of street lighting and exterior electrical distribution, Department of Water Supply, Gas, and Electricity, City of New York, N. Y., died September 10, 1939, instead of September 10, 1940, as incorrectly reported in the November issue, page 474.

Membership

Recommended for Transfer

The board of examiners, at its meeting on November 14, 1940, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Gardett, H. C., chief electrical engineer and general manager, Bureau of Power and Light, Los Angeles, Calif.

1 to Grade of Fellow

To Grade of Member

Anderson, L. G., superintendent of rolling stock and shops, Indianapolis Railways, Indianapolis, Ind.
Bateman, I. L., assistant engineer of distribution, Bureau of Power and Light, Los Angeles, Calif.
Bauman, H. A., assistant superintendent, Brooklyn Edison Company, Brooklyn, N. Y.
Cockaday, L. M., instructor of physics, United States Naval Academy, Annapolis, Md.
DeBlieux, E. V., design engineer, General Electric Company, Pittsfield, Mass.
Dingle, Howard, president, Cleveland Worm and Gear Company, Cleveland, Ohio.
Kleinau, C. S., engineer, Southern California Telephone Company, Los Angeles, Calif.
Marrison, W. A., research engineer, Bell Telephone Laboratories, New York, N. Y.
Matthews, W. J., chief operator, Virginia Electric and Power Company, Fredericksburg, Va.
Montgomery, T. B., control engineer, Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Poling, C. V., assistant electrical engineer, Tennessee Valley Authority, Knoxville, Tenn.
Rapp, Stanley, protection engineer, Pacific Telephone and Telegraph Company, San Francisco, Calif.
Smalley, D. F., electrical engineer, General Electric Company, West Lynn, Mass.
Ver Planck, D. W., assistant professor of electrical engineering, Yale University, New Haven, Conn.
Weeks, F. D., assistant engineer, Commonwealth Edison Company, Chicago, Ill.

15 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before December 31, 1940, or February 28, 1941, if the applicant resides outside of the United States or Canada.

United States

1. North Eastern

Dubinsky, B. A. M., General Electric Company, Schenectady, N. Y.
Foley, E. P., New York, New Haven and Hartford Railroad Company, New Haven, Conn.
Goetzl, M., Central New York Power Corporation, Syracuse, N. Y.
Macintyre, J. R., General Electric Company, West Lynn, Mass.
Spaulding, A. E., General Electric Company, Lynn, Mass.
Walker, I., Walker Electrical Supply Company, Worcester, Mass.
White, J. F., New York, New Haven and Hartford Railroad, New Haven, Conn.

2. Middle Eastern

Adams, E., City Electrician, Mansfield, Ohio.
Affanasiev, K. J. (Member), Pennsylvania Water and Power Company, Baltimore, Md.
Askin, W. T., United States Navy Department, Cleveland, Ohio.
Clark, O. S. (Member), Copper Wire Engineering Association, Washington, D. C.
Dawson, A. A., Public Service Commission of Virginia, Charleston, W. Va.
Edwards, H. E., Westinghouse Electric and Manufacturing Company, Mansfield, Ohio.
Gore, J. W., Bethlehem Steel Company, Baltimore, Md.
Howard, W. J., Columbus and Southern Ohio Electric Company, Columbus, Ohio.
Jedrziewski, A. A., West Penn Power Company, Greensburg, Pa.
Koslow, J., Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Quatman, F. T., North Electric Manufacturing Company, Galion, Ohio.
Raybould, G. M., Reliance Electric and Engineering Company, Cleveland, Ohio.
Richmond, N. E., The Autocall Company, Shelby, Ohio.
Silberman, A. H., Philadelphia Electric Company, Philadelphia, Pa.
Stephens, R. L., Navy Department, Bureau of Ships, Washington, D. C.
Warford, H. S., Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.

3. New York City

Barker, G. A. (Member), Johns-Mansville Sales Corporation, New York, N. Y.
Eichna, O. L., Arma Corporation, Brooklyn, N. Y.
Hight, S. C., Bell Telephone Laboratories, New York, N. Y.
Humber, J. H., Arnessen Electric Company, New York, N. Y.
Miller, R. J., Consolidated Edison Company of New York, Inc., New York, N. Y.
Monti, L. P. (Member) Underwriters' Laboratories, Inc., New York, N. Y.
Moore, J. A. (Member), Board of Transportation, BMT Division, Brooklyn, N. Y.
Orfanos, C. J. G., Public Service Electric and Gas Company, Newark, N. J.
Parkinson, G., Gibbs and Cox, Inc., New York, N. Y.
Pearson, H. A., Sonotone Corporation, Elmsford, N. Y.
St. John, J. H., Heyer Products Company, Belleville, N. J.

4. Southern

Hardin, L. H. (Member), South Carolina Public Service Authority, Charleston, S. C.
King, L. A., Clemson College, Clemson, S. C.
McSwain, E. G., Oxford Orphanage, Oxford, N. C.

5. Great Lakes

Bailey, J. L., Southeastern Indiana Power Company, Shelbyville, Ind.
Comee, L. M., Cutler-Hammer, Inc., Milwaukee, Wis.
Gremillion, B. X. (Member), Indiana Bell Telephone Company, Indianapolis, Ind.
Morton, J. H. (Member), Consulting Engineer, Detroit, Mich.
Oliphint, J. W., Westinghouse Electric and Manufacturing Company, Detroit, Mich.
Rutemiller, O. G. (Member), Westinghouse Electric and Manufacturing Company, Detroit, Mich.
Taylor, O. R., American Telephone and Telegraph Company, Chicago, Ill.
Tighe, T. J., General Electric Company, Jackson, Mich.
Winter, L. A. (Member), Buell and Winter Engineering Company, Sioux City, Iowa.
Youngdahl, C. H., Carnegie-Illinois Steel Company, Chicago, Ill.

6. North Central

Kenyon, J. S., Public Service Company of Colorado, Denver, Colo.
Thomas, D., Loup Power District, Columbus, Nebr.

7. South West

Barnard, C. F., General Electric X-Ray Corporation, Tulsa, Okla.
Cuadra, M. J., Missouri Gas and Electric Service Company, Lexington, Mo.
Curry, O. B., Kansas Gas and Electric Company, Wichita, Kans.
Eaton, C. B., Texas Electric Service Company, Eastland, Tex.
Forsman, M. E., American Smelting and Refining Company, El Paso, Tex.
Plog, K., American Telephone and Telegraph Company, Wichita, Kans.

8. Pacific

Tillin, I., East Bay Transit Company, Oakland, Calif.

9. North West

Gallotte, W. A., Puget Sound Power and Light Company, Seattle, Wash.
Kucera, C. F., Washington Water Power Company, Spokane, Wash.
Madden, G. T., Puget Sound Power and Light Company, Seattle, Wash.
Small, L. C., Washington Water Power Company, Spokane, Wash.

10. Canada

Hobbs, G. P., Defence Industries, Limited, Nobel, Ont.
Noakes, F., University of Toronto, Toronto, Ont.
Partello, T. E., Hydro Electric Power Commission, Toronto, Ont.

Total, United States and Canada, 63

Elsewhere

Mahmud, S. S., Public Works Department, Mohlan, Sheikhupura, India.
Palmer, W. C., Frontino Gold Mines Limited, Segovia, Antioquia, Republic of Colombia.

Total, elsewhere, 2

Of Current Interest

National Resources Board Seeks Roster of Scientific Personnel

According to information recently released over the signature of Leonard Carmichael, director, the United States Government through the National Resources Planning Board is now engaged in developing a "Roster of Scientific and Specialized Personnel for the purpose of providing a comprehensive list of highly trained Americans possessing special ability in their respective fields." The roster is reported as being jointly administered by the National Resources Planning Board and the United States Civil Service Commission, with representatives of the National Research Council, the Social Science Research Council, the American Council of Learned Societies, the American Council on Education, and other national societies as members of an advisory committee. James C. O'Brien of the staff of the United States Civil Service Commission is listed as executive officer of the project, and Leonard Carmichael is listed as director.

The information necessary for the development of the proposed roster is being secured through the circulation of questionnaires in various engineering, scientific, and technical channels. Although the letter of transmittal with the questionnaire now being circulated through electrical-engineering channels makes no reference to national defense, national defense was the basis of assistance and co-operation recently requested of President R. W. Sorensen and National Secretary H. H. Henline of AIEE incidental to the preparation of the "technical check list" and distribution of it and the Planning Board's questionnaire for electrical engineers. In this assistance and co-operation these officers have made no direct or implied obligation upon the membership, as each member of course has the privilege of handling his questionnaire as he sees fit.

Committee for Child Refugees Will Continue Work

To learn first hand the attitude of the British government toward the evacuation of children from the war zone, Eric H. Biddle, vice-president and executive director of the United States Committee for the Care of European Children, Inc., recently made an air trip to England for conferences with British authorities and other persons active in public life. Mr. Biddle has reported that he "received the most eloquent evidence of the warm appreciation which leaders of the government of Great Britain feel for the generosity of the American people in offering thousands of homes for British children."

It is Mr. Biddle's opinion that some official program for the overseas evacuation of British children, suspended for the time being because of weather and other hazards in the North Atlantic, will be resumed in the spring of 1941. Meanwhile, a limited number of children will be sent by their parents on regular passenger sailings. Hence, the activities of the United States Committee (*EE, Sept. '40, p. 382*) are to be continued.

The Committee, Mr. Biddle's report states, "will keep a relatively small staff on duty at its national headquarters, 215 Fourth Avenue, New York, N. Y., to carry out its continuing responsibilities for the children who have come to this country under its auspices. . .

"The Committee is now responsible to the parents in England for 1,000 children . . . and has a moral responsibility for at least 3,000 other children who have arrived independently. . . . The young guests who have been brought here under the auspices of the United States Committee have been placed in 40 different communities, with New York, N. Y., Boston, Mass., Rochester, N. Y., Worcester, Mass., Philadelphia, Pa., and Canton, Ohio, having received the greatest numbers.

"The United States Committee is studying the possibilities of evacuation of children from countries in the war zone other than Great Britain. Enormous practical difficulties stand in the way, but all possibilities will be studied."

Education • • •

Defense Training for Engineers To Be Financed by Government

A $9,000,000 program for intensive training of personnel for the defense needs of Government and industry in the United States is to be carried on through qualified engineering schools, according to recent announcement from the Federal Security Agency, United States Office of Education. Text of the announcement follows.

Accepting the almost unanimous offers of American engineering schools to assist in the training of defense personnel, Paul V. McNutt, administrator of the Federal Security Agency, today announced plans for the establishment in qualified educational institutions of special courses, to be given at Government expense, for the intensive training of over 30,000 students with technical backgrounds, to meet future needs of both industry and Government in carrying out the defense program.

Funds to finance this program were voted by Congress in the recent supplementary defense appropriation act, which provides $9,000,000 to be expended for this purpose under the direction of John W. Studebaker, United States commissioner of education, who is also giving general supervision to a companion program of vocational training in the nation's vocational schools. Allotments will be made to the co-operating institutions to meet expenses incurred in giving instruction under the plan.

Courses of study will be given by the colleges both for those able to devote their entire time to preparation for future defense jobs and for workers now employed who desire to fit themselves for more responsible assignments. All instruction will be of college grade equivalent to that given regular candidates for a degree, but the special courses, which will require from two to eight months of study, will concentrate upon training of immediate practical application to specific defense jobs. Classes will be held both at the engineering schools and in or near industrial plants for the benefit of part-time and evening students. The regular college teaching staffs will be supplemented by additional teachers, including specially qualified men from the industries to be served.

TYPE OF TRAINING

Actual and potential needs for additional technical and supervisory personnel will determine the specific courses to be offered and every effort will be made to maintain a continuous balance between the supply of trainees and demands for their services. The first courses to be established will be designed to forestall potential shortages of inspectors of materials, chemicals, explosives, instruments, and power units; designers of machinery, equipment, tools and dies, and aircraft power plants, structures, and instruments; production engineers and supervisors; physical metallurgists; marine engineers and naval architects. As other needs become apparent, additional courses will be added to this program.

Qualifications for enrollment will be determined by the institutions giving the courses in accordance with general rules suggested by the United States Office of Education. In most cases, students will be selected from those who have previously had some technical training or its equivalent in practical experience which must be refreshed or supplemented to fit them to perform specific technical or supervisory duties. The program will not conflict with the vocational training courses also being administered by the Office of Education through the several State boards for vocational education, nor will it displace regular undergraduate courses given by the co-operating colleges.

COLLEGES SUGGEST COURSES

Participation in the program is limited to institutions that offer regular engineering curricula leading to a degree and which operate under charters exempting them from taxation. About 150 engineering schools in State universities, land-grant colleges, and private colleges and universities are eligible. Those desiring to take part have already been invited to submit preliminary plans stating the need for trained technicians in

their areas, the facilities and personnel they have available for giving the necessary courses, the number of students that can be taught, and the approximate cost of instruction. These purposes will be adjusted to a co-ordinated plan for the country as a whole, after which authorization will be given to proceed with the enrollment of students. An announcement of the first courses to be offered, and the institutions where they will be available, will be made about November 15, and instruction should begin shortly thereafter.

Federal allotments to the participating colleges may be used to meet the costs of salaries, materials and supplies, reference books, the operation of buildings, the maintenance and repair of equipment, and, to a limited extent, the purchase or rental of additional equipment and the leasing of space in noncollege buildings. No expenditures are authorized for the purchase or construction of buildings, nor is provision made to defray the living expenses of students. Students will pay no tuition charges.

DEFENSE NEEDS STUDIED

The training program is the outgrowth of several months of preliminary investigation by the United States Office of Education into needs for technically trained personnel. During the past summer a preliminary survey of the situation was made by Andrey A. Potter, dean of the school of engineering of Purdue University, working with Federal agencies and with industries in the defense program. This is now being supplemented by sample investigations in specific areas, including New York City, Philadelphia, Pittsburgh, Chicago, and San Francisco, under the direction of Dean Potter, H. P. Hammond, dean of engineering, Pennsylvania State College; Thorndike Saville, dean of engineering, New York University; and Professor B. M. Woods, department of mechanical engineering, University of California. The data so obtained will guide in determining the first courses to be given, and the methods to be used in determining further needs.

Further to determine training needs as they develop, the Office of Education has just completed arrangements under which selected colleges and universities have made available 22 regional advisers (see accompanying table) who will serve without compensation. Each of these will act, within his own territory, as a liaison officer maintaining continual contact with defense industries, Army and Navy district offices, employment services, and other sources of information on personnel needs, as well as with local engineering schools equipped to meet demands for training courses as they arise. These men will keep the Washington headquarters continually informed so that deficiencies in any one region may be met, if necessary, by training students in other places where facilities are available. In this way a national program will be evolved that will continually adjust itself to changing conditions both in industry and as regards the technical personnel requirements of the Federal Government. Authorization of courses not only will conform to the needs so developed, but also will take into account the staff, equipment, and buildings at the various institutions and the availability of qualified students.

As the program develops arrangements will be made to facilitate the placement of students in defense positions as they complete their training. Much of this will be done by direct contacts between the engineering schools and near-by industries, but students will also have available the facilities of State and Federal employment offices and the United States Civil Service Commission.

Closely co-operating in the development of the program is the advisory committee on engineering training for national defense, the appointment of which was announced by Commissioner Studebaker on September 26 (*EE, Nov. '40, p. 478*). Assisting Commissioner Studebaker and Doctor Fred J. Kelly, chief of the division of higher education, under whose immediate jurisdiction the program falls, will be a small staff of specialists now being selected.

Engineering Defense Training—Regional Advisers

Adviser	Institution	Area for Supervision	Region Number
Dean E. L. Moreland	Massachusetts Institute of Technology, Cambridge	Maine, Massachusetts, New Hampshire, and Vermont	1
Prof. L. E. Seeley	Yale University, New Haven, Conn.	Connecticut and Rhode Island	2
Dean S. C. Hollister	Cornell University, Ithaca, N. Y.	New York State (except New York City)	3
Dean J. W. Barker	Columbia University, New York, N. Y.	New York City and Long Island	4
Pres. A. R. Cullimore	Newark College of Engineering, Newark, N. J.	Northern New Jersey	5
W. T. Spivey	Drexel Institute of Technology, Philadelphia, Pa.	Eastern Pennsylvania, southern New Jersey, and Delaware	6
Dean S. S. Steinberg	University of Maryland, College Park	District of Columbia and eastern Maryland	7
Dean Blake R. Van Leer	North Carolina State College, Raleigh	North Carolina, South Carolina, and Virginia	8
Prof. J. E. McDaniel	Georgia School of Technology, Atlanta	Alabama, Florida, Georgia, Mississippi, and eastern Tennessee	9
Dean F. L. Wilkinson, Jr.	University of Louisville, Louisville, Ky.	Kentucky, Southern Ohio, and southwestern half of West Virginia	10
J. D. Beatty	Carnegie Institute of Technology, Pittsburgh, Pa.	Western half of Pennsylvania, northeastern half of West Virginia and western Maryland	11
Dean C. E. MacQuigg	Ohio State University, Columbus	Northern half of Ohio	12
Dean H. B. Dirks	Michigan State College, Lansing	Southern Michigan	13
Pres. D. B. Prentice	Rose Polytechnic Institute, Terre Haute, Ind.	Indiana (except for Chicago industrial area)	14
Pres. H. T. Heald	Illinois Institute of Technology, Chicago	Illinois, southern Wisconsin, and the Chicago industrial area in Indiana	15
Prof. H. O. Croft	University of Iowa, Iowa City	Iowa, Minnesota, Nebraska, North Dakota, South Dakota, northern Wisconsin, and northern Michigan	16
Dean R. A. Seaton	Kansas State College, Manhattan	Arkansas, Kansas, Missouri, Oklahoma, western Tennessee	17
Dean W. R. Woolrich	University of Texas, Austin	Louisiana and Texas (east of Pecos River)	18
Pres. M. F. Coolbaugh	Colorado School of Mines, Golden	Colorado and Wyoming	19
Prof. R. L. Daugherty	California Institute of Technology, Pasadena	Arizona, New Mexico, southern California, and Texas (west of Pecos River)	20
Dean S. B. Morris	Stanford University, Stanford University, Calif.	Northern California, Nevada, and Utah	21
Prof. H. H. Langdon	State College of Washington, Pullman	Idaho, Montana, Oregon, and Washington	22

Lighting Conference at University of Texas. The College of Engineering at the University of Texas, Austin, will sponsor the first Southwest Lighting Conference, to be held at the University January 9–11, 1941. Fluorescent light sources and their application and other recent developments in lighting techniques will be featured on the program. Conference participants will include members of the southwest section of the Illuminating Engineering Society, architects, representatives of the lighting industry, and members of the Texas State Department of Health.

Notes on List of Accredited Curricula

(See Facing Page)

(*a*). Accrediting applies to both the day and evening curricula.

(*b*). Accrediting applies to the 4-year and 5-year curricula leading to the bachelor of science degree.

(*c*). Accrediting applies to day curriculum only. Action on evening curriculum deferred pending granting of degrees.

(*d*). Accrediting applies only to curriculum as submitted to ECPD and upon completion of which a certificate is issued by Harvard University certifying that the student has pursued such a curriculum.

(*e*). The accrediting of a curriculum in general engineering implies satisfactory training in engineering sciences and in the basic subjects pertaining to several fields of engineering; it does not imply the accrediting, as separate curricula, of those component portions of the curriculum such as civil, mechanical, or electrical engineering that are usually offered as complete professional curricula leading to degrees in these particular fields.

(*f*). On July 24, 1940, Illinois Institute of Technology was formed by the consolidation of Armour Institute of Technology and Lewis Institute. Curricula now listed under Illinois Institute of Technology were formerly listed under Armour Institute of Technology.

List of Undergraduate Curricula Accredited by ECPD as of October 24, 1940

(Subject to revision. For basis of accrediting see ELECTRICAL ENGINEERING, December 1938, page 515, report of ECPD eighth annual meeting elsewhere in this issue.)

University of Alabama: Aeronautical, civil, electrical, industrial, mechanical, mining

Alabama Polytechnic Institute: Electrical, mechanical

University of Alaska: Civil

University of Arizona: Civil, electrical, mechanical, mining

University of Arkansas: Civil, electrical, mechanical

Brooklyn Polytechnic Institute: Chemical (day and 8-year evening), civil (*a*), electrical (*a*), mechanical (*a*)

Brown University: Civil, electrical, mechanical

Bucknell University: Civil, electrical, mechanical

University of California: Civil, electrical, mechanical, metallurgical (metallurgy), mining, petroleum

California Institute of Technology: Aeronautical (5- and 6-year courses), chemical (5-year course), civil, electrical, mechanical

Carnegie Institute of Technology: Chemical, civil (*a*), electrical (*a*), industrial (management) (*a*), mechanical (*a*), metallurgical (*a*)

Case School of Applied Science: Chemical, civil, electrical, mechanical, metallurgical

Catholic University of America: Aeronautical, architectural, civil, electrical

University of Cincinnati: Aeronautical, chemical, civil, electrical mechanical.

The Citadel: Civil

Clarkson College of Technology: Chemical, civil, electrical, mechanical

Clemson Agricultural College: Civil, electrical, mechanical

College of the City of New York (*a*): Civil, electrical, mechanical

University of Colorado: Architectural, civil, electrical, mechanical

Colorado School of Mines: Geological, metallurgical, mining, petroleum

Colorado State College: Civil, electrical, mechanical

Columbia University (*b*): Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

University of Connecticut: Civil, electrical

Cooper Union Institute of Technology (*c*): Civil, electrical, mechanical

Cornell University: Chemical, civil, electrical, industrial (administrative), mechanical

Dartmouth College: Civil

University of Delaware: Civil, electrical, mechanical

University of Denver: Electrical

University of Detroit: Aeronautical, architectural, chemical, civil, electrical, mechanical

Drexel Institute: Chemical, civil, electrical, mechanical

Duke University: Civil, electrical, mechanical

University of Florida: Civil, electrical, industrial, mechanical

Georgia School of Technology: Aeronautical, chemical (including co-operative curriculum), civil, electrical, mechanical

George Washington University: Civil, electrical, mechanical

Harvard University (*d*): Civil, communication, electrical, industrial (engineering and business administration), mechanical, metallurgical (physical metallurgy), sanitary

University of Idaho: Civil, electrical, mechanical, metallurgical (metallurgy), mining

University of Illinois: Architectural, ceramic (technical option), chemical, civil, railway civil, electrical, railway electrical, general (*e*) mechanical, railway mechanical, metallurgical, mining

Illinois Institute of Technology (Armour College of Engineering) (*f*): Chemical, civil, electrical, mechanical

Iowa State College: Agricultural, architectural, ceramic, chemical, civil, electrical, general (*e*), mechanical

State University of Iowa: Chemical, civil, electrical, mechanical

Johns Hopkins University: Chemical, civil, electrical, mechanical

University of Kansas: Architectural, civil, electrical, mechanical, mining

Kansas State College: Agricultural, architectural, civil, electrical, mechanical

University of Kentucky: Civil, electrical, mechanical, metallurgical, mining

Lafayette College: Civil, electrical, industrial (administrative), mechanical, metallurgical, mining

Lehigh University: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining

Louisiana State University: Chemical, civil, electrical, mechanical, petroleum

University of Louisville: Chemical, civil, electrical, mechanical

University of Maine: Civil, electrical, general (*e*), mechanical

Manhattan College: Civil, electrical

Marquette University: Civil, electrical, mechanical

University of Maryland: Civil, electrical, mechanical

Massachusetts Institute of Technology: Aeronautical, building engineering and construction, chemical, civil, electrical, electrochemical, general (*e*), industrial (business and engineering administration), mechanical, metallurgical (metallurgy), naval architecture and marine engineering (including marine transportation), public health, sanitary

University of Michigan: Aeronautical, chemical, civil, electrical, engineering mechanics, mechanical, metallurgical, naval architecture and marine engineering, transportation

Michigan College of Mining and Technology: Civil, electrical, mechanical, metallurgical, mining

Michigan State College: Civil, electrical, mechanical

University of Minnesota: Aeronautical, chemical, civil, electrical, mechanical, metallurgical, mining, petroleum

University of Missouri: Chemical, civil, electrical, mechanical

Missouri School of Mines and Metallurgy: Ceramic, civil, electrical, metallurgical, mining (mine) (including petroleum option)

Montana School of Mines: Geological, metallurgical, mining

Montana State College: Civil, electrical, mechanical

University of Nebraska: Agricultural, architectural, civil, electrical, mechanical

University of Nevada: Electrical, mechanical, mining

University of New Hampshire: Civil, electrical, mechanical

University of New Mexico: Civil, electrical, mechanical

New Mexico State College: Civil, electrical, mechanical

New Mexico School of Mines: Geological (both mining and petroleum options), metallurgical, mining, petroleum

New York University: Aeronautical, chemical (day and 7-year evening), civil (*a*), electrical (*a*), industrial (administrative), mechanical

New York State College of Ceramics (at Alfred University): Ceramic

Newark College of Engineering: Civil, electrical, mechanical

North Carolina State College: Ceramic, civil, electrical, mechanical

University of North Dakota: Chemical, civil, electrical, mechanical, mining

North Dakota Agricultural College: Architectural, mechanical

Northeastern University: Civil, electrical, industrial, mechanical

Northwestern University: Civil, electrical, mechanical

Norwich University: Civil, electrical

Ohio State University: Ceramic, chemical, civil, electrical, industrial, mechanical, metallurgical, mining (mine)

University of Oklahoma: Architectural, chemical, civil, electrical, mechanical, petroleum

Oklahoma Agricultural and Mechanical College: Civil, electrical, industrial, mechanical

Oregon State College: Civil, electrical, mechanical

University of Pennsylvania: Chemical, civil, electrical, mechanical

Pennsylvania State College: Architectural, ceramic (ceramics), chemical, civil, electrical, electrochemical, fuel technology, industrial, mechanical, metallurgical (metallurgy), mining, petroleum and natural gas, sanitary

University of Pittsburgh: Chemical, civil, electrical, industrial, mechanical, metallurgical, mining, petroleum

Pratt Institute: Electrical, mechanical

Princeton University: Chemical, civil, electrical, mechanical

Purdue University: Chemical, civil, electrical, mechanical

Rensselaer Polytechnic Institute: Aeronautical, chemical, civil, electrical, industrial, mechanical, metallurgical

Rhode Island State College: Civil, electrical, mechanical

Rice Institute: Civil, electrical, mechanical

University of Rochester: Mechanical

Rose Polytechnic Institute: Civil, electrical, mechanical

Rutgers University: Civil, electrical, mechanical, sanitary

University of Santa Clara: Civil, electrical, mechanical

South Dakota State College: Civil, electrical, mechanical

South Dakota State School of Mines: Civil, electrical, metallurgical, mining

University of Southern California: Petroleum

Southern Methodist University: Civil, electrical, mechanical

Stanford University: Civil, electrical, mechanical, metallurgical, mining, petroleum

Stevens Institute of Technology (*e*): General

Swarthmore College: Civil, electrical, mechanical

Syracuse University: Chemical, civil, electrical, industrial (administrative), mechanical

University of Tennessee: Chemical, civil, electrical, mechanical

University of Texas: Architectural, civil, electrical, mechanical, petroleum (petroleum production)

Agricultural and Mechanical College of Texas: Civil, electrical, mechanical, petroleum (4- and 5-year courses)

Texas Technological College: Civil, electrical, mechanical

Tufts College: Civil, electrical, mechanical

Tulane University of Louisiana: Civil, electrical, mechanical

University of Tulsa: Petroleum (including options in refining and production)

Union College: Civil, electrical

United States Coast Guard Academy (*e*): General

University of Utah: Civil, electrical, mechanical, metallurgical, mining

Utah State Agricultural College: Civil

Vanderbilt University: Civil, electrical, mechanical

University of Vermont: Civil, electrical, mechanical

University of Virginia: Civil, electrical, mechanical

Virginia Military Institute: Civil, electrical

Virginia Polytechnic Institute: Ceramic, chemical, civil, electrical, industrial, mechanical

Washington University: Architectural, civil, electrical, industrial (administrative), mechanical

University of Washington: Aeronautical, ceramic, chemical, civil, electrical, mechanical, metallurgical, mining

State College of Washington: Architectural, civil, electrical (basic and hydroelectric options), mechanical (basic option), metallurgical, mining

Webb Institute of Naval Architecture: Naval architecture and marine engineering

West Virginia University: Civil, electrical, mechanical, mining

University of Wisconsin: Chemical, civil, electrical, mechanical, metallurgical, mining

Worcester Polytechnic Institute: Civil, electrical, mechanical

Yale University: Chemical, civil, electrical, mechanical, metallurgical (metallurgy)

Honors • • • •

John Fritz Medal Awarded to Ralph Budd

The John Fritz Medal, conferred by the four national societies of civil, electrical, mechanical, and mining and metallurgical engineers in recognition of notable scientific and industrial achievement, has been awarded for 1941 to Ralph Budd, president of the Chicago, Burlington, and Quincy Railroad, for "improvement of railroad tracks and service, especially the introduction of lightweight streamlined trains."

Mr. Budd was born August 20, 1879, at Waterloo, Iowa, and received the degree of bachelor of science in civil engineering at Highland Park College in 1899. He was with the engineering department of the Chicago Great Western Railway, 1899–1902, and with the Chicago, Rock Island, and Pacific Railway, 1902–06, advancing to division engineer. From 1906 to 1909 he was chief engineer of the Panama Railroad, and from 1909 to 1912 chief engineer of the Oregon Trunk Railway, Spokane, Portland, and Seattle Railway, and the Spokane and Inland Empire Railroad. He went with the Great Northern Railway in 1913 as assistant to the president and chief engineer, becoming executive vice-president in 1918 and president in 1919. Since 1932 he has been president of the Chicago, Burlington, and Quincy Railroad and its various subsidiaries. During 1930 he inspected and reported upon rehabilitation of railways in the Soviet Union. He is a member of the American Society of Civil Engineers, American Railway Engineering Association, and Western Society of Engineers.

Regarded as the highest honor of the engineering profession, the John Fritz Medal is awarded not oftener than once a year, without restriction on account of nationality or sex, by a joint board composed of four members from each of the founder societies. AIEE representatives on the present board, all past presidents, are: A. M. MacCutcheon (A'12, F'26), W. H. Harrison (A'20, F'31), John C. Parker (A'04, F'12), F. M. Farmer (A'02, F'13).

Other Societies •

NRC Insulation Conference Held in Washington, D. C.

With a registered attendance of 102, the 13th annual session of the National Research Council's conference on electrical insulation was held in Washington, D. C. from October 30 to November 2, 1940. The Friday morning technical session was held at the National Bureau of Standards, the other three technical sessions were held in the National Research Council's rooms in the National Academy of Sciences building.

The opening general session was addressed by Doctor Ross G. Harrison, chairman of National Research Council, and by Doctor Vannevar Bush, vice-chairman of NRC's division of engineering and industrial research and chairman of the National Defense Research Commission. Doctor Harrison briefly outlined the 77-year history of the National Academy of Sciences and explained the relationship of National Research Council as the Academy's operating agency. He pointed out that National Research Council, set up in 1916 as a consulting body to study the scientific aspects of World War problems, was made a permanent organization in 1918 to stimulate research on national defense and other problems of broad importance. Doctor Bush explained more of Council's activities, pointing out that it functions to bring together diverse groups of scientific thought, with special emphasis on problems of national significance. In necessarily general terms Doctor Bush indicated something of the scope and importance of Council's work incidental to current national defense problems and its co-operation with such other vital agencies as the National Advisory Committee on Aeronautics and the National Defense Research Commission, a suborganization of the Council of National Defense, the purpose of which is to accelerate civilian research for the benefit of government.

By official action, Doctor Ward F. Davidson (A'14, F'26) director of research for the Consolidated Edison Company of New York, Inc., will continue as chairman of the insulation conference. With new appointments and holdover officers, the executive committee of the conference now is constituted as follows:

W. F. Davidson, Consolidated Edison Company, New York, N. Y., chairman

S. O. Morgan, Bell Telephone Laboratories, New York, vice-chairman

Thorstein Larsen, Consolidated Edison Company, New York, secretary

H. H. Race, General Electric Company, Schenectady, N. Y., chairman, committee on physics

Arthur von Hipple, Massachusetts Institute of Technology, Cambridge, vice-chairman, committee on physics

R. N. Evans, Consolidated Edison Company, New York, chairman, committee on chemistry

G. T. Kohman, Bell Telephone Laboratories, New York, vice-chairman, committee on chemistry

C. F. Hill, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa., chairman, committee on monographs

H. N. Curtis, Bureau of Standards, Washington, D. C.

W. A. Del Mar, Phelps Dodge Copper Products Corporation, Yonkers, N. Y.

J. B. Whitehead, The Johns Hopkins University, Baltimore, Md.

Continuing its customary practice, the conference included on its Washington program 22 informal technical presentations in the nature of progress reports indicating the status and trend of physical, chemical, and electrical research of significance in the field of electrical insulation. It is expected that a comprehensive report reflecting the nature and scope of the material presented at Washington will be available for an early issue of ELECTRICAL ENGINEERING.

The date and location of the 1941 conference was left open, pending developments.

ECPD Elects Officers at Annual Meeting

At the 1940 annual meeting of the Engineers' Council for Professional Development held on October 24 at the University Club, Pittsburgh, Pa., R. E. Doherty (A'16, F'39) president, Carnegie Institute of Technology, was elected chairman and Harry T. Woolson, executive engineer, the Chrysler Corporation, was elected vice-chairman. George T. Seabury, secretary of the American Society of Civil Engineers, becomes secretary and H. H. Henline (A'19, M'26) national secretary, AIEE, assistant secretary. The following committee chairmen also were elected at the Pittsburgh meeting:

A. A. Potter, past president, The American Society of Mechanical Engineers, *committee on engineering schools*

Charles F. Scott (A'92, F'25, HM'29) past president AIEE, Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners, *committee on professional recognition*

R. L. Sackett, past president, SPEE, *committee on student selection and guidance*

S. D. Kirkpatrick, editor, *Chemical and Metallurgical Engineering, committee on professional training*

E. R. Needles, of Ash-Howard-Needles and Tammen, New York, N. Y., *ways and means committee.*

ENGINEERING INSTITUTE OF CANADA BECOMES MEMBER

By unanimous vote of the Council, the Engineering Institute of Canada became the eighth participating body of ECPD. A delegation of members of the Institute, headed by Past President J. B. Challies, was present. Dr. Challies, speaking on behalf of the president of the EIC, expressed the Institute's appreciation of the action by which it had become more closely affiliated with engineering bodies in the United States and announced the names of the Institute's representatives: J. M. R. Fairbairn, A. Surveyer, and J. B. Challies, all past presidents of the Institute. He also introduced the other members of the delegation, Professor C. R. Young, of the University of Toronto, who was appointed to the commit-

Future Meetings of Other Societies

American Association for the Advancement of Science. December 27, 1940–January 2, 1941, Philadelphia, Pa.

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 17–20, 1941, New York, N. Y.

American Mathematical Society. 47th Annual Meeting, December 31, 1940–January 1, 1941, New Orleans, La.

American Physical Society. 238th meeting, December 1940, Pasadena, Calif.

239th meeting (annual), December 26–28, 1940, Philadelphia, Pa.

240th meeting, February 21–22, 1941, Cambridge, Mass.

American Society of Civil Engineers. Annual meeting, January 15–18, 1941, New York, N. Y.

American Society for Testing Materials. Spring meeting, March 3–7, 1941, Washington, D. C.

American Society of Heating and Ventilating Engineers. 47th annual meeting, January 27–29, 1941, Kansas City, Mo.

Engineering Institute of Canada. Annual meeting, February 6–7, 1941, Hamilton, Ont., Canada.

Institute of Radio Engineers. 16th annual convention, January 9–11, 1941, New York, N. Y.

National Exposition of Power and Mechanical Engineering, 14th. December 2–7, 1940, New York, N. Y.

Society of Automotive Engineers. Annual meeting, January 6–10, 1941, Detroit, Mich.

tee on professional training; H. F. Bennett, who becomes a member of the committee on student selection and guidance; and L. Austin Wright, general secretary, EIC. James A. Vance, who was not present, will serve on the committee on professional recognition.

REPORTS STATUS OF ACCREDITING

For the committee on engineering schools, whose principal function has been the accrediting of curricula, Dean Potter reported as chairman. Incident to its accrediting program the committee has given advice informally to schools requesting it. As of October 20, 1939, curricula to the number of 433 had been accredited unconditionally, 82 for a limited period, and, 172 had not been accredited. During 1939–40 visits were made to 22 institutions for the purpose of reinspecting 70 curricula on the accredited list, and 17 institutions were visited in order to appraise 32 curricula not on the accredited list. As a result of the year's work and of actions taken on October 24, 1940, the record now stands as follows: Total curricula submitted, including reinspections, 791; accredited unprovisionally, 457; accredited provisionally, 83; not accredited, 164; reinspections resulting in no change in status, 82; action pending, 5. A complete list of accredited curricula appears on page 523.

Competition for 1941 Prizes Announced by EEI Committee

Prizes to be awarded at the 1941 convention of the Edison Electric Institute recently have been announced by means of posters distributed to public-utility operating companies throughout the United States. The awards, contributed by various donors and administered by the prize awards committee of EEI, constitute the electric light and power industry's recognition of outstanding achievements by companies and individuals. Competition is open to all companies and their employees without regard to membership in EEI.

Thirty-three prizes will be awarded, 11 to electric utility companies and 22 to individuals. Most recently established is the Laura McCall Award offered for the first time this year, and consisting of a plaque and two certificates to companies for home-service department achievement in promoting electrical appliances and home lighting, and cash prizes to $100, $50, and $25 to the heads of the departments responsible.

The Augustus D. Curtis Award, for new lighting installations or complete relighting of commercial interiors, has been broadened this year to include use of fluorescent lighting, either entirely or in combination with incandescent sources. The award includes certificates to the companies winning first and second places, and prizes of $200 and $100 respectively to the individuals responsible, as well as third and fourth prizes of $50 and $25 to individuals.

Of particular interest to AIEE members are the Forbes prize, a cash award of $250 for the best paper on public relations in the electric light and power industry, and the McGraw prizes, three awards of $250, $150, and $100, for the best papers on technical or engineering subjects relating to the industry. Any person employed by an electric light and power company may compete.

Full information on all awards may be obtained from the secretary, Edison Electric Institute, 420 Lexington Ave., New York, N. Y. The other awards are:

The Charles A. Coffin Award, a gold medal and a contribution of $1,000 to the employees' benefit fund, to the public-utility operating company showing the greatest over-all advancement in operations and physical plant.

The Thomas W. Martin Award, a bronze plaque, given to the company showing the greatest contribution to progress in rural electrification.

The National Electric Water Heating Award, cash prizes of $500, $300, and $200, to companies for best all-around promotion and sale of electric water heaters.

The George A. Hughes Award, trophy and two certificates of recognition to companies, cash awards of $500, $300, and $200 to individuals responsible, for development of the electric-range market through direct or co-operative promotion or selling.

The R. B. Marshall Award, five cash prizes of $100 each to salesmen representing utility companies, classified in five groups according to number of customers, who sell, lease, or rent the greatest number of domestic electric ranges.

The Claude L. Matthews Awards for Valor, three cash awards of $100 each for acts of outstanding courage performed in maintaining or restoring electric service.

IES Sets up Regional Divisions

As a result of constitutional changes effective October 1, 1940, the Illuminating Engineering Society has established eight territorial divisions, known as "regions". Geographical boundaries have been set according to natural groupings of the sections and chapters of the society. Regional meetings are to be scheduled during the coming year.

Under the new plan, which resembles the setup of the larger national engineering societies, each region will be represented on the society's council by a regional vice-president. Chairmen of sections will no longer be members of the council. For the year 1940–41, vice-presidents have been chosen by nominating committees representing the sections and chapters in each region and confirmed by the council. Beginning in 1941, candidates for regional vice-presidents are to be chosen by regional nominating committees and voted upon by the entire membership. Four vice-presidents will be elected each year, to serve two-year terms.

The regions, and their vice-presidents for 1940–41, are:

Region A, Toronto section, Montreal chapter, non-section territory in Canada; R. M. Love, Canadian General Electric Company, Toronto.

Region B, New England and New York sections; O. P. Cleaver (A'36) Westinghouse Lamp Division, Bloomfield, N. J.

Region C, Philadelphia and Pittsburgh sections Baltimore-Washington chapter; A. S. Turner, Jr., General Electric Company, Philadelphia, Pa.

Region D, western New York, Cleveland, Ohio Valley, and Michigan sections; A. F. Wakefield, F. W. Wakefield Brass Company, Vermilion, Ohio.

Region E, southeastern United States, including Georgia and New Orleans chapters; R. A. Palmer, Duke Power Company, Charlotte, N. C.

Region F, Chicago and Twin-City sections, Nebraska-Iowa, Heart of America, and Spirit of St. Louis chapters; N. B. Hickox, Chicago, Ill.

Region G, southwestern United States, including southwestern section; F. M. Rutherford, Dallas Power and Light Company, Dallas, Tex.

Region H, Pacific Coast area, including Southern California and San Francisco Bay sections; F. A. Hansen (M'31) Western Institute of Light and Vision, Los Angeles, Calif.

Engineering Section, AAAS, to Hold Annual Meeting

"Economic and Engineering Interests of the Americas" will be the chief theme of the annual meeting of Section M (Engineering) of the American Association for the Advancement of Science, to be held at Philadelphia, Pa., December 31, 1940. The program, arranged in co-operation with Director G. H. Cox, Inter-American Center, The George Washington University, is expected to include addresses on "Aviation Progress" by Doctor Jerome C. Hunsaker, Massachusetts Institute of Technology; "Educational Relationships Between the Americas", by Doctor Clyde Heck Marvin, president, The George Washington University; "The Press and Inter-American Relationships", by Raymond C. Clapper; "Engineering Developments in South America", by Fred Lavis, consulting engineer; "Inter-American Engineering Standards", by C. L. Warwick, secretary, American Society for Testing Materials. Further information about the meeting, which is open to all those interested, may be obtained from F. M. Feiker (M'34), secretary, Section M, AAAS, and dean of the school of engineering, The George Washington University, Washington, D. C.

South American Tour Planned by NRC

Plans are being developed by the National Research Council to have a group of industrial and research executives from the United States visit South American countries early in 1941 to study industrial possibilities and means of interchanging technological developments. The Council has been assured co-operation from the government agencies responsible for inter-American relations. Tours of laboratories in the United States and in several European countries have been sponsored by the Council in previous years.

Industry • • • •

New Standards Bring Smaller Motors

New standards adopted October 1 by the National Electrical Manufacturers Association have reduced the frame sizes of electric motors in sizes from three-quarters to two horsepower. This is said to be the first major change in the original motor-dimension standards adopted by the association members 12 years ago, and represents the culmination of advances in engineering art and materials of motor manufacture achieved during that period. These changes affect weight, space, and size, and are made possible largely by two major improvements: better silicon steels; and new synthetic and cloth insulations having

higher dielectric strength and requiring less space.

Since the adoption of the new standards, both the General Electric Company and the Westinghouse Electric and Manufacturing Company have announced new lines of motors: an entire line of completely new polyphase induction motors in "integral horsepower" sizes by the former; and a series ranging from one-half to three horsepower by the latter. Principal new features of the new motors are: modern "streamlined" appearance; more complete physical protection than heretofore available except in enclosed machines; improved insulation resulting in smaller motor coils; and improved bearing design and lubricating arrangements.

G. B. Cortelyou Dies. George Bruce Cortelyou, retired president of the former Consolidated Gas Company, New York, N. Y. (now part of Consolidated Edison Company of New York) died October 26, 1940. Born at New York, N. Y., July 26, 1862, he received the degrees of bachelor of laws, Georgetown University, 1895, and master of laws, Columbian (now George Washington) University, 1896, and the honorary degree of doctor of laws from several institutions. He entered government service in 1889, serving as secretary to various officials of the Port of New York and the Postoffice Department in New York and later in Washington, D. C. From 1895 to 1901 he was secretary successively to Presidents Cleveland, McKinley, and Theodore Roosevelt, and in 1903 he was appointed by President Roosevelt to the newly created Cabinet position of Secretary of Commerce and Labor, later serving as Postmaster General, and as Secretary of the Treasury. He continued in the last position until the end of the Roosevelt administration. From 1909 until his retirement in 1935 he was president of the Consolidated Gas Company. He was a past president of the American Gas Association, the former National Electric Light Association, and the Edison Electric Institute.

E. T. J. Brandon Dies. Edgar Thomas John Brandon, retired chief electrical engineer of the Hydro Electric Power Commission of Ontario, Toronto, died September 25, 1940. Born at Toronto, December 20, 1880 he received the degree of bachelor of applied science from the University of Toronto in 1901. He was a design engineer for the Ontario Power Company, and later with W. C. Johnson, consulting engineer, both at Niagara Falls, and with Hugh L. Cooper in New York, N. Y., before entering the employ of the Commission in 1908 as a designer. Prior to his retirement on account of ill health in 1938, Mr. Brandon was a Fellow of the AIEE, and active in the Toronto Section, of which he was chairman 1916–17.

G.E. Lightning Generator Dismantled. The 40-ton lightning generator which provided the lightning display at the General Electric Company's Steinmetz Hall at the New York World's Fair was dismantled after the close of the Fair. The equipment was divided, part being sent to the high-voltage laboratory of the National Bureau of Standards, Washington, D.C., for construction of a similar 2,000,000-volt lightning generator, and the remainder replacing equipment now in use at the company's high-voltage laboratory at Pittsfield, Mass.

Electric Pump Wins Plastics Award. An all-molded electric bilge pump received the highest award in the transport group of the fifth annual modern plastics competition sponsored by *Modern Plastics* magazine. Awards were announced in October. Made of Durez, a phenolic plastic, by Oris Manufacturing Company, the pump has high dielectric strength and is resistant to water, oil, and abrasives. The automatic motor-controlled unit handles 70 gallons per ampere hour of battery used. Designed for use on either sail or motor boats 50 feet long or less, the pump is 10 inches high, occupies a floor area $5^1/_2$ by $3^1/_2$ inches, and has a sway-proof switch which turns it on and off as needed, regardless of the motion of the boat.

Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

An Analysis of the Unbalanced Wye Circuit

To the Editor:

The unbalanced or unsymmetrical three-phase circuit, either delta- or wye-connected, can be analyzed completely by means of complex-quantity algebra or by graphics. The usual treatment appears to be algebraic, several variations of this form of attack being available in standard textbooks on electrical engineering. However, whereas the unbalanced delta circuit is also discussed by way of graphics, the authors of this discussion never have seen a graphical solution for the general wye circuit. Statements in textbooks often imply the impossibility of such an analysis.

However, the wye-circuit, with no neutral lead, and with unbalanced line voltages and leg impedances, is open readily to graphics. Such a treatment in general does not require greater time in solving a problem than do other methods, and it has the distinct added advantage of permitting visualization of the entire problem and the individual steps as one proceeds. The following graphical method of solving the unbalanced wye circuit is, so far as the authors know, the only one that is *completely* graphical and comparable with the graphical methods obtained for the unbalanced delta circuit.

Figure 1*a* shows an unbalanced wye-connected load receiving its power from a three-phase generator. The line voltage of 100 volts, and the ohmic values of the circuit elements, are chosen to give convenient magnitudes and phase angles. To a voltage scale the full lines of figure 1*b* show the triangle of line voltages and the three component leg voltages with point N being the generator neutral.

If the generator neutral N is connected to the load junction O a current will flow in the neutral line. This current can be determined easily by familiar methods, either graphical or algebraic. When the switch in the neutral line is opened, the neutral current then becomes zero, and a voltage E_{ON} appears across the switch, figure 1*a*. With the neutral of the generating system fixed, the existence of this voltage shows that the potential of point O no longer is the same as that of N, but that O has moved on the vector diagram, as shown by the voltage vector E_{ON} of figure 1*b*. The fundamental problem in the analysis of the unbalanced wye circuit is that of determining the position of O.

If a single-phase voltage were introduced into the neutral line in place of the switch, this voltage being equal in magnitude to E_{ON} and of the same phase, exactly the same circuit conditions would prevail as though the neutral line were open. The analysis thus can be carried out by superposing the results for the balanced leg voltages and those for the single-phase voltage. The single-phase voltage acts on the three leg impedances in parallel, sending a resultant current through them, equal and opposite to the initial neutral current. E_{ON} is merely the product of the initial neutral current and the equivalent impedance of the three legs in parallel. It thus is known directly in magnitude and phase.

The steps in solving the unbalanced wye circuit to determine the location of O are:

1. Determine the magnitude and phase of the neutral current assuming the neutral line closed.

2. Calculate the voltage E_{ON}, in magnitude and phase, which will drive the above current through the three leg impedances connected in parallel.

3. Lay off the voltage E_{ON} in proper phase from the initial point N. The outer end of the vector voltage is the position of O.

The remaining steps in determining the actual leg voltages, currents, phase angles, power components, etc., for the unbalanced wye circuit then follow directly.

The method is illustrated on the circuit of figure 1*a*, and although complex-quantity algebra can be employed wholly or in part, the analysis here is given by graphics. With phase rotation ABC, and positive phase angles measured counterclockwise, the neutral current when the switch is closed is $10/\sqrt{3}$ amperes, figure 2*a*. Conventions with respect to directions of voltage and current and the order of subscripts on these quantities are shown in figure 1*a*.

The voltage E_{ON} which will drive the current $10/\sqrt{3}$ amperes through the parallel combination of the three leg impedances, figure 2*b*, can be obtained by the usual

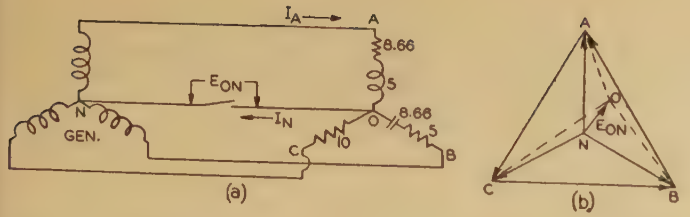

Figure 1. Unbalanced wye-connected load with associated voltage vector diagram

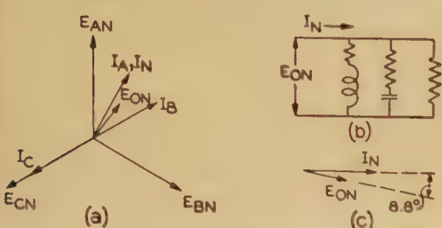

Figure 2. Load circuit of the single-phase voltage E_{ON} with associated vector diagram

graphical method of handling a parallel circuit. It is found to be 24 volts and lags the current I_N by 8.8 degrees, figure 2*c*. Point O thus is located upward and to the right from point N, figure 1*b*. The vector voltage E_{ON} is 51.2 degrees from the horizontal. As already stated, the remaining steps in determining all quantities now follow immediately.

This method also is applicable to a three-phase system of unequal line voltages. Further, the point N can be assumed anywhere, inside or outside the triangle of line voltages. It can, for example, be chosen at A, B, or C, if it appears convenient. The respective parts of the graphical solution are carried out as described, and O will be located, regardless of the magnitude or kind of unbalance, or the assumption on the position of N. For any particular circuit O can have, of course, but one location on the graph and all methods must yield the same result. The several steps in this method perhaps may be carried out more conveniently by complex quantity algebra if one desires. In any case, the scheme visualizes the problem and its component parts, which other methods do not do so successfully.

B. L. Robertson (A'26, M'32)
and L. J. Black

(Respectively, associate professor and instructor of electrical engineering, University of California, Berkeley)

Value of a Determinant With Complex Elements

To the Editor:

During the past few years, there have appeared in the literature a number of articles on the application of matrix algebra to electrical problems. In all of these papers, the use of the inverse of a square matrix is involved. This in turn requires the finding of the value of the determinant of the matrix. The determination of the value of a determinant with real elements (that is, with elements which are constants) presents no problem since such determinants have been considered in a course in analytic geometry. A determinant with complex elements, however, is usually new to the reader and the process of determining its value by the ordinary rules of expansion is not only quite laborious for the higher-order determinants, but it might present a problem as to what to do with the complex elements. The purpose of this letter is to suggest three simple methods of reducing a determinant with complex elements to a sum of determinants with real elements only.

"Sum of two determinants" method

This method is based upon the fundamental rule for adding two determinants differing only by one column or one row. Only the second order and the third order determinants will be discussed here as the higher order determinants follow directly. Consider a second order determinant

$$\begin{array}{cc} A+jB & C+jD \end{array}$$
$$\begin{vmatrix} R_{11}+jX_{11} & R_{12}+jX_{12} \\ R_{21}+jX_{21} & R_{22}+jX_{22} \end{vmatrix} \quad (1)$$

If the column containing R_{11}, R_{21} is represented by A, the column containing jX_{11}, jX_{21} by jB, etc., then with this new notation the determinant (1) can be written very simply

$$|A+jB,\ C+jD| \quad (2)$$

Now apply the rule for addition of determinants successively,

$$|A+jB,\ C+jD| = |A,\ C+jD| + |jB,\ C+jD| = |A,\ C| + |A, jD| + |jB,\ C| + |jB, jD| \quad (3)$$

If all the elements of any column have a common factor, this factor may be divided out and placed before the new determinant. Then, taking the j and the $j^2=-1$ out, equation 3 becomes

$$|A+jB,\ C+jD| = |A,\ C| - |B,\ D| + j|A,\ D| + j|B,\ C| \quad (4)$$

that is

$$\begin{vmatrix} R_{11}+jX_{11}, & R_{12}+jX_{12} \\ R_{21}+jX_{21}, & R_{22}+jX_{22} \end{vmatrix} = \begin{vmatrix} R_{11}, & R_{12} \\ R_{21}, & R_{22} \end{vmatrix} - \begin{vmatrix} X_{11}, & X_{12} \\ X_{21}, & X_{22} \end{vmatrix} + j\begin{vmatrix} R_{11}, & X_{12} \\ R_{21}, & X_{22} \end{vmatrix} + j\begin{vmatrix} X_{11}, & R_{12} \\ X_{21}, & R_{22} \end{vmatrix} \quad (5)$$

Thus, the steps involved are:

1. Expand the determinant with the new notation as shown in (3).
2. Simplify by taking the j's out as shown in (4).
3. Substitute the columns of R's and X's for A, B, C, and D as shown in (5).

To illustrate further this method and the two methods following, next consider the third order determinant,

$$\begin{array}{ccc} A+jB & C+jD & E+jF \end{array}$$
$$\begin{vmatrix} R_{11}+jX_{11} & R_{12}+jX_{12} & R_{13}+jX_{13} \\ R_{21}+jX_{21} & R_{22}+jX_{22} & R_{23}+jX_{23} \\ R_{31}+jX_{31} & R_{32}+jX_{32} & R_{33}+jX_{33} \end{vmatrix} = |A+jB,\ C+jD,\ E+jF| \quad (6)$$

Following the procedure outlined previously gives

$$\begin{aligned} |A+jB, C+jD, E+jF| &= |A, C+jD, E+jF| + |jB, C+jD, E+jF| \\ &= |A, C, E+jF| + |A, jD, E+jF| + |jB, C, E+jF| + |jB, jD, E+jF| \\ &= |A, C, E| + |A, C, jF| + |A, jD, E| + |A, jD, jF| + |jB, C, E| + |jB, C, jF| + |jB, jD, E| + |jB, jD, jF| \\ &= |A, C, E| - |A, D, F| - |B, C, F| - |B, D, E| + j\{|A, C, F| + |A, D, E| + |B, C, E| - |B, D, F|\} \end{aligned} \quad (7)$$

From which

$$\begin{array}{ccc} A+jB & C+jD & E+jF \end{array}$$
$$\begin{vmatrix} R_{11}+jX_{11} & R_{12}+jX_{12} & R_{13}+jX_{13} \\ R_{21}+jX_{21} & R_{22}+jX_{22} & R_{23}+jX_{23} \\ R_{31}+jX_{31} & R_{32}+jX_{32} & R_{33}+jX_{33} \end{vmatrix} =$$

$$\begin{array}{c} A\ \ C\ \ E \\ \begin{vmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{vmatrix} \end{array} - \begin{array}{c} A\ \ D\ \ F \\ \begin{vmatrix} R_{11} & X_{12} & X_{13} \\ R_{21} & X_{22} & X_{23} \\ R_{31} & X_{32} & X_{33} \end{vmatrix} \end{array} - \begin{array}{c} B\ \ C\ \ F \\ \begin{vmatrix} X_{11} & R_{12} & X_{13} \\ X_{21} & R_{22} & X_{23} \\ X_{31} & R_{32} & X_{33} \end{vmatrix} \end{array} -$$

$$\begin{array}{c} B\ \ D\ \ E \\ \begin{vmatrix} X_{11} & X_{12} & R_{13} \\ X_{21} & X_{22} & R_{23} \\ X_{31} & X_{32} & R_{33} \end{vmatrix} \end{array} + j\begin{array}{c} A\ \ C\ \ F \\ \begin{vmatrix} R_{11} & R_{12} & X_{13} \\ R_{21} & R_{22} & X_{23} \\ R_{31} & R_{32} & X_{33} \end{vmatrix} \end{array} + j\begin{array}{c} A\ \ D\ \ E \\ \begin{vmatrix} R_{11} & X_{12} & R_{13} \\ R_{21} & X_{22} & R_{23} \\ R_{31} & X_{32} & R_{33} \end{vmatrix} \end{array} +$$

$$j\begin{array}{c} B\ \ C\ \ E \\ \begin{vmatrix} X_{11} & R_{12} & R_{13} \\ X_{21} & R_{22} & R_{23} \\ X_{31} & R_{32} & R_{33} \end{vmatrix} \end{array} - j\begin{array}{c} B\ \ D\ \ F \\ \begin{vmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{vmatrix} \end{array} \quad (8)$$

The number of determinants on the right-hand side of the equation should be equal to the 2^n where n is the order of the original determinant.

"Complex notation" method

It is interesting to note that the expansion 4 is similar to the form when expanding the product of two complex numbers

$$(A+jB)(C+jD) = AC - BD + j(AD+BC) \quad (9)$$

This is to be expected since the terms in the expansion of a second-order determinant involve the products of two complex numbers. Likewise, the form 7 will be found similar to that when expanding the product of three complex numbers

$$(A+jB)(C+jD)(E+jF) = ACE - ADF - BCF - BDE + j(ACF + ADE + BCE - BDF) \quad (10)$$

After having determined the form 9 or 10, it is only necessary to follow step 3 as given in the first method.

"Combination" method

Another method of reducing a determinant with complex elements to a sum of determinants with real elements only is to start with the R and X determinants and then form all possible combinations of columns of R's and jX's. That is, replace the columns of R's by their corresponding columns of jX's one at a time, then two at a time, then three at a time, etc. In the case of the third-order determinant, equation 8, start with

$$\begin{vmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{vmatrix}, \quad \begin{vmatrix} jX_{11} & jX_{12} & jX_{13} \\ jX_{21} & jX_{22} & jX_{23} \\ jX_{31} & jX_{32} & jX_{33} \end{vmatrix}$$

Now replace the columns of the R determinant by their corresponding columns of the

X determinant, one at a time. This gives

$$\begin{vmatrix} R_{11} & R_{12} & jX_{13} \\ R_{21} & R_{22} & jX_{23} \\ R_{31} & R_{32} & jX_{33} \end{vmatrix}, \quad \begin{vmatrix} R_{11} & jX_{12} & R_{13} \\ R_{21} & jX_{22} & R_{23} \\ R_{31} & jX_{32} & R_{33} \end{vmatrix}, \quad \begin{vmatrix} jX_{11} & R_{12} & R_{13} \\ jX_{21} & R_{22} & R_{23} \\ jX_{31} & R_{32} & R_{33} \end{vmatrix}$$

Next two columns at a time,

$$\begin{vmatrix} R_{11} & jX_{12} & jX_{13} \\ R_{21} & jX_{22} & jX_{23} \\ R_{31} & jX_{32} & jX_{33} \end{vmatrix}, \quad \begin{vmatrix} jX_{11} & jX_{12} & R_{13} \\ jX_{21} & jX_{22} & R_{23} \\ jX_{31} & jX_{32} & R_{33} \end{vmatrix}, \quad \begin{vmatrix} jX_{11} & R_{12} & jX_{13} \\ jX_{21} & R_{22} & jX_{23} \\ jX_{31} & R_{32} & jX_{33} \end{vmatrix}$$

Then three at a time,

$$\begin{vmatrix} jX_{11} & jX_{12} & jX_{13} \\ jX_{21} & jX_{22} & jX_{23} \\ jX_{31} & jX_{32} & jX_{33} \end{vmatrix}$$

It can be seen that by starting with the R determinant and ending with the X determinant, the result is the eight determinants on the right-hand side of equation 8. The factor before each determinant can be found in the following manner. If the determinant has one column of jX's, the factor is $+j$. If the determinant has two columns of jX's, the factor is $+j^2=-1$. And if the determinant has three columns of jX's, the factor is $+j^3=-j$.

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(Assistant professor, department of electrical engineering, Ohio State University, Columbus)

Books Received •

"Experiments With Light". A new manual containing practical problems for students in science has been prepared under the direction of the Illuminating Engineering Society. Designed for use in high-school physics courses, the manual outlines a dozen practical experiments with light which may be worked out by the student with simple low-cost material, locally obtainable or easily built. The book attempts to give a better concept of the fundamentals of light already studied and a knowledge of the practical problems of lighting as an aid to seeing in everyday life. "Experiments With Light" may be obtained from the Illuminating Engineering Society, 51 Madison Avenue, New York, N. Y., at 25 cents per copy.

The following new books are among those recently received at the engineering Societies Library. Unless otherwise specified, books listed bave been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

ENGINES OF DEMOCRACY. By R. Burlingame. Charles Scribner's Sons, New York, 1940. 606 pages, illustrated, 9½ by 6 inches, cloth, $3.75. The history of modern America is viewed in the light of its technological advancement. As the developments in metallurgy, electrical communication, power, printing, highways, illumination, chemical synthesis, and so on, are reviewed, their contribution to our present way of life is stressed. The book closes with a discussion of modern trends and of the social inventions that must follow the technical ones. Contains a bibliography, a chronological list of events and inventions, and extensive index.

HANDBOOK OF ENGLISH IN ENGINEERING USAGE. By A. C. Howell. Second edition. John Wiley and Sons, New York, 1940. 433 pages, illustrated, 8 by 5 inches, cloth, $2.50. Presents rules for proper English, covering word selection, sentence construction, style, arrangement, punctuation, and grammar. Succeeding chapters discuss the composition of business letters, reports, and technical magazine articles. Examples from published material are included to demonstrate current practice.

INTRODUCTION TO ELECTRICAL ENGINEERING. By G. V. Mueller. McGraw-Hill Book Company, New York, 1940. 306 pages, illustrated, 9½ by 6 inches, cloth, $2.75. Points out the relations, the mathematical expression of the relations, and the graphical interpretations of the expressions in each type of circuit—electric, magnetic, and dielectric—under transient as well as steady-state conditions. Particular attention is paid to the solution of nonlinear resistance circuits as an approach to the solution of magnetic circuits. Typical oscillograms are used to illustrate important principles. Problems and laboratory experiments.

INVENTORS AND ENGINEERS OF OLD NEW HAVEN. (New Haven Tercentenary Publications.) Edited by R. S. Kirby. New Haven Colony Historical Society, New Haven, Conn., 1939. 111 pages, illustrated, diagrams., 10 by 6 inches, cloth, apply to R. S. Kirby, Yale University. Contains six lectures given under the auspices of the School of Engineering in Yale University. The subjects are: Eli Whitney; early New Haven inventors; early Yale inventors; early Yale engineers; the formative years of New Haven's public utilities; the founding of the Sheffield Scientific School.

TELEVISION BROADCASTING. By L. R. Lohr, with a foreword by D. Sarnoff. McGraw-Hill Book Company, New York, 1940. 274 pages, illustrated, 9 by 6 inches, cloth, $3.00. Discusses various aspects of television broadcasting, including its effect on society; operating techniques and equipment; program considerations, especially the economic, legal, and technical problems; the co-ordination required for presentation; and the advertising potentialities. Appendices contain a typical television script with production directions, and the Federal Communications Commission rules governing stations.

MARINE DIESEL ENGINE STANDARDS. Edited by M. J. Reed and O. A. Sibley. Published by Diesel Engine Manufacturers' Association, New York, N. Y., 1940. 141 pages, diagrams, 9½ by 6 inches, cloth, $2.00. In addition to presenting standard practices for all phases of installation and application of Diesel engines and accessories in marine work, this book also gives information on standard performances and definitions, classification and marine inspection, and includes some statistical material.

TROUBLES OF ELECTRICAL EQUIPMENT. By H. E. Stafford. Second edition. McGraw-Hill Book Company, New York, 1940. 373 pages, illustrated, 9 by 6 inches, cloth, $3.00. Covers the symptoms, causes, and remedy of troubles of the a-c and d-c apparatus found in the average industrial plant. Also includes hints on efficient operation and maintenance. Diagrams are extensively used, and all formulas are illustrated by practical examples.

WILEY TRIGONOMETRIC TABLES. New York, John Wiley and Sons, 1940. 81 pages, tables, 9 by 5½ inches, cloth, $0.75. Aims to present the tables most used by students of trigonometry. The tables are: squares and square roots; constants with their common logarithms; natural logarithms of numbers; five-place logarithms of numbers; logarithms of functions; and four-place values of functions and radians.

VECTOR METHODS, APPLIED TO DIFFERENTIAL GEOMETRY, MECHANICS, AND POTENTIAL THEORY. By D. E. Rutherford. Oliver and Boyd, Edinburgh and London; Interscience Publishers, New York, 1939. 127 pages, diagrams, 7½ by 5 inches, cloth, 4s 6d, $1.50. Intended to provide for undergraduate use a clear account of the abstract theory of the vector calculus and a brief but broad survey of the applications of the theory to various branches of pure and applied mathematics.

THEORY OF GROUP CHARACTERS AND MATRIX REPRESENTATIONS OF GROUPS. By D. E. Littlewood. Oxford University Press, New York; Clarendon Press, Oxford, England, 1940. 292 pages, diagrams, etc., 10 by 6½ inches, cloth, $5.50. Presents a simple, self-contained account of the theory of group characters in its application to finite and continuous matrix groups, and elaborates some of its applications. Preliminary chapters on matrices, algebras. and groups precede the development of the theory. Applications to the theory of symmetric functions and to the structure of groups are dealt with in some detail. In the last two chapters the theory is generalized to certain continuous matrix groups. Bibliography and character tables.

SILVER IN INDUSTRY. Edited by L. Addicks. Reinhold Publishing Corporation, New York, 1940. 636 pages, illustrated, 9 by 6 inches, cloth, $10.00. A summary of three years' research on silver and its industrial applications is presented in 20 chapters written by the editor and others. Topics include physical and mechanical properties, alloys, commercial production, silver-coating methods, electrical and catalytic applications, corrosion properties, and the use of silver in bearings, germicides, photography, coinage, the decorative arts. Bibliography, serial list of United States patents, and classified list of patents of all countries.

MAKING YOUR PHOTOGRAPHS EFFECTIVE. By J. A. Lucas and B. Dudley. McGraw-Hill Book Company (Whittlesey House), New York, 1940. 385 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Discusses all phases of photographic work. Fundamental processes, cameras, and other equipment, darkroom construction, and print making are described; exposures and lighting problems considered; and various methods of work presented.

WEATHER ANALYSIS AND FORECASTING. A Textbook on Synoptic Meteorology. By S. Petterssen. McGraw-Hill Book Company, New York, 1940. 505 pages, illustrated, 9 by 6 inches, cloth, $5.00. Presents modern methods of weather analysis and forecasting. The author discusses in detail the underlying theories and their application to weather charts and upper-air charts, with examples of correct analysis and forecasts. Recent results in air-mass analysis, frontal analysis, and isentropic analysis are included. Bibliography.

AIRCRAFT YEAR BOOK FOR 1940. 22d edition. Edited by H. Mingos. Aeronautical Chamber of Commerce of America, New York, 1940. 532 pages, illustrated, 9 by 6 inches, cloth, $5.00. This annual provides a record of developments in aviation during the past year, both in the United States and abroad. The work of the Army, Navy, various Federal agencies, and commercial firms is reviewed. Chapters are devoted to the present war, air lines, private flying, airports, training, and other fields of interest. The book includes tables of aircraft specifications, descriptions of aircraft and engine designs, a chronology of events and records, an aeronautical directory, and statistics of the industry.

AEROPLANE INSTRUMENTS, Part I; LANDING LEGS, WHEELS, AND BRAKES; AIRSCREWS, Part I. Aeroplane Maintenance and Operation Series, volumes II, III, and IV. Edited by E. Molloy and E. W. Knott. Chemical Publishing Company, New York, 1940. Each 132 pages, illustrated, 9 by 6 inches, cloth, $2.00 each. Three volumes of a new series on airplane maintenance and operation. "Aeroplane Instruments (Part I)" deals with the operation and maintenance of the Sperry gyropilot, Sperry aircraft instruments, and Smith's aircraft instruments. "Landing Legs, Wheels and Brakes" deals with the maintenance and repair of various commercial types of landing equipment, including landing legs, shock absorbers, tail-wheel units, brakes, and tires. "Airscrews (Part I)" deals with the maintenance and repair of the de Havilland controllable-pitch airscrews and hydromatic airscrews.

ELECTRICAL CIRCUITS AND MACHINERY. Volume I. Direct Currents. By F. W. Hehre and G. T. Harness. John Wiley and Sons, New York, 1940, 513 pages, illustrated, 9 by 6 inches, cloth, $4.50. Volume one of a two-volume treatment of electric circuits and machinery offered as a successor to the textbook with that title written by Morecroft and Hehre in 1933. Like its predecessor, it is intended as an introductory text for students of electrical engineering and a general text for others. Contains a chapter on electronics.

ELECTRICAL ENGINEERING LABORATORY EXPERIMENTS. By C. W. Ricker and C. E. Tucker. Fourth edition. McGraw-Hill Book Company, New York and London, 1940. 458 pages, diagrams, etc., 9 by 6 inches, cloth, $3.00. Revised and expanded, this edition of a well-known guide includes 70 experiments, with accounts of theory and procedure.

FRENCH-ENGLISH SCIENCE DICTIONARY. For Students in Agricultural, Biological and Physical Sciences. By L. De Vries. McGraw-Hill Book Company, New York, 1940. 546 pages, 7 by 5 inches, fabrikoid, $3.50. Contains 43,000 scientific terms with the English equivalents. While intended to meet the needs of students of agriculture, biology, and physics, it should be useful to students and translators in any field of science.

GEOMAGNETISM. By S. Chapman and J. Bartels. Oxford University Press, New York; Clarendon Press, Oxford, England, 1940. Two volumes, 1049 pages, diagrams, etc., 9½ by 6½ inches, cloth, $18.00. Aims to provide an account of present knowledge for workers in geomagnetism, cosmic-ray physics, geophysical prospecting, and radio communication. Volume I gives a detailed description of the observed facts of geomagnetism and the ways in which they are measured, together with brief accounts of lunar and solar motions, the properties of the sun's atmosphere, earth currents, the aurora, the earth's upper atmosphere, and magnetic prospecting. Volume II discusses the analysis and synthesis of geomagnetic data and the physical theories which attempt to explain the facts. Bibliography.

GRAPHISCHE METHODEN ZUR LÖSUNG VON WECHSELSTROMPROBLEMEN. By A. von Brunn. Benno Schwabe and Company, Verlag, Basel, Switzerland, 1938. 243 pages, diagrams, etc., 10 by 6½ inches, cloth, 18 Swiss fr. Graphical methods for the solution of a-c problems are presented in a comprehensive manner. After discussing the fundamental theory and vectorial representation of the physical elements of electric circuits, the author develops the general methods of graphical calculation and many specific adaptations. Bibliography and list of symbols.

Transactions

Preprint of Papers and Discussions Comprising Pages 369–416 of the 1940 Volume

The Application of Traction Motors

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Synopsis: The application of traction motors is based fundamentally on speed-time curve calculations. This method has been used for many years and is familiar to electrical engineers engaged primarily in transportation activities. Many other engineers infrequently encounter problems of traction-motor application but are not conversant with the effect which variations in service conditions produce on vehicle performance. This paper points out certain recent changes in transportation requirements tending toward greater standardization of equipment, and summarizes the effects of varying operating conditions. The broad basis of economical application is indicated.

THE application of all types of traction motors is based fundamentally on the speed-time curve. Speed-time curve calculations may be unnecessary for many specific applications, but a knowledge of the principles is essential to correct application of motors. The methods of calculation are covered fully in textbooks and for many years have been included in college courses in railway engineering. The purpose of this paper is to illustrate the application of the principles and show the effect on traction-motor performance of varying the more important determining factors.

In the past few years the business of electric transportation has undergone important changes. These have produced changes in apparatus requiring a different technique in application. Until the year 1928 surface cars, rapid-transit cars, and light traction locomotives were propelled by axle-mounted motors driving through single-reduction gears. At that time the lines of traction motors ranged from 25 to 250 horsepower, and the work of application consisted largely of the motor and gear ratio selection to meet the particular service requirements. For this it was usually necessary to calculate the service performance of the motor, chosen on the basis of the engineer's judgment. Motors were self-ventilated and while attention had to be paid to commutating requirements under the most severe conditions of operation and to short-time overloads, the ability to operate within the motor's continuous rating generally insured satisfactory all-around performance. The steady decrease in the cost of energy and increase in car operators' wages had reduced energy consumption to a secondary position instead of one of prime importance which it had occupied 25 years before.

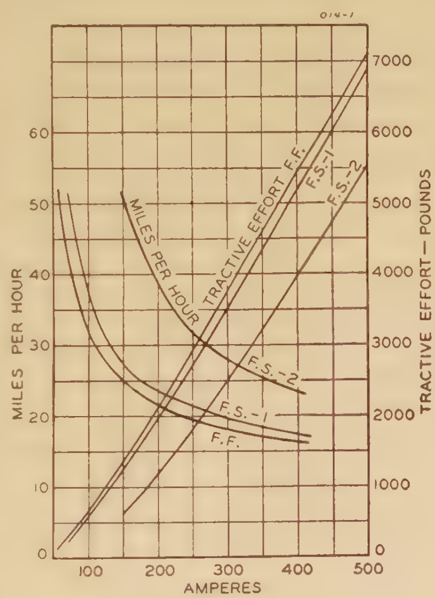

Figure 1. Trolley-coach motor A

Gear ratio, 10.61:1; wheel diameter, 40 inches; volts, 550

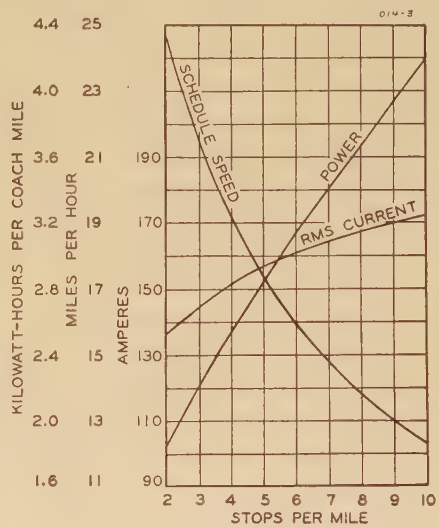

Figure 3. Trolley-coach operating characteristic

Motor *A*, F.S.-1 field strength, normal acceleration and braking

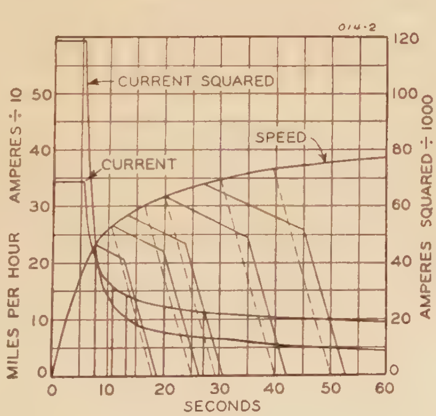

Figure 2. Trolley-coach performance curves

Motor *A*, F.S.-1 field strength, normal acceleration and braking

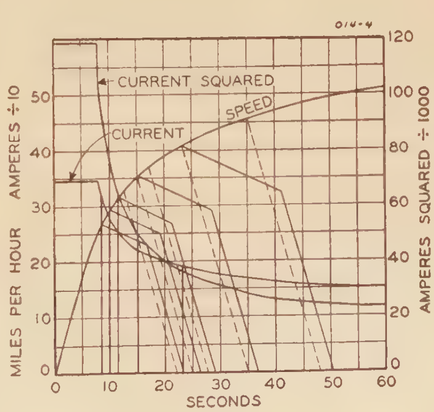

Figure 4. Trolley-coach performance curves

Motor *A*, F.S.-2 field strength, normal acceleration and braking

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Paper 40-14, recommended by the AIEE committee on transportation, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted October 23, 1939; made available for preprinting December 11, 1939; released for final publication February 23, 1940.

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Street Cars

Today street-car and trolley-coach motors are of the light-weight high-speed highly ventilated type. Short-time overloads and accelerating currents must be given more detailed examination. Also standardization of vehicles and equipments has progressed. Practically all city street cars purchased are of the Presidents' Conference Committee or similar type utilizing the same electrical equipment. This was the outgrowth of several years' study. All cars are of nearly the same weight and use the same gear ratio and wheel diameter. A study of operating conditions throughout the country was made and the electrical equipment was then designed to meet the maximum safe speed, balancing speed, and acceleration and electric braking rates specified by the committee and to have adequate capacity for the most severe service likely to be encountered. With such standardization, applications to specific cities obviously involve little additional work.

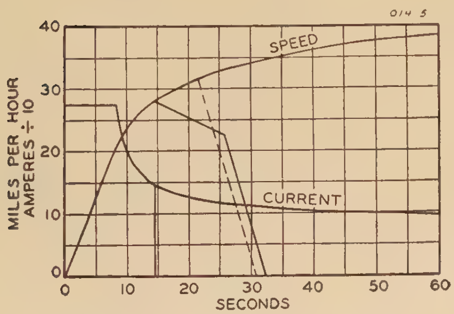


Figure 5. Reduced acceleration rate

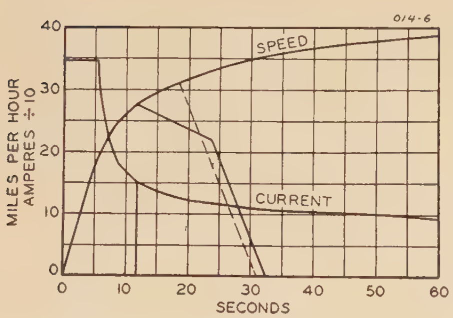


Figure 6. Reduced braking rate

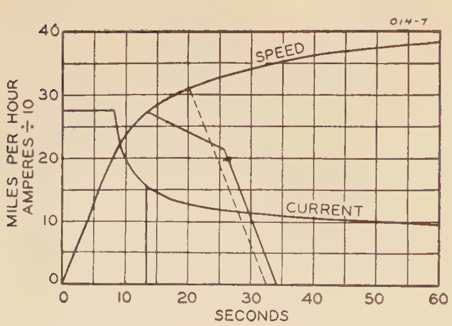


Figure 7. Reduced acceleration and braking rates

Figures 5–7. Trolley-coach performance curves

Motor *A*, F.S.-1 field strength

Trolley Coaches

Trolley coaches came into prominence in 1928. Two sizes are in common use: 30- to 33-passenger and 38- to 44-passenger capacity. The 30-passenger coach is propelled by one 65-horsepower series motor and the 40-passenger coach by two such motors, one 125-horsepower series motor, or one 140-horsepower compound motor. The rear axle of the 30-passenger coach generally has worm drive with 10.25:1 gear reduction. The rear axle of the 40-passenger two-motor coach is generally a double-bowl worm-drive axle or a single-bowl double-reduction axle with a gear ratio of about 9.25:1, depending on the axle manufacturer. The single-motor 40-passenger trolley coaches all have double-reduction axles with gear ratios of approximately 9.25, 10.5, and 11.5 available. Also, the single motor may be used with or without dynamic braking and with different degrees of field shunting. The equipment best suited for a specific application can be determined by economic analysis, comparing the total fixed charges and operating expenses of the various alternatives. Performance calculations are required for this comparison.

While trolley coaches are not standardized to the same degree as street cars, the weights for the same capacity do not differ widely. Hence, when a motor is designed for trolley-coach service, definite effort is made to cover the probable field of application and generally only one capacity of motor is available. Evidently much progress toward standardization has been made.

Performance Calculation

Generalizations regarding the performance of traction motors are frequently misleading. It is safe to say that increased weight of the vehicle always increases energy consumption and increased duration of stop always decreases schedule speed, all other factors remaining unchanged. But the change of any one factor may automatically change some other factor. For instance, if the weight is changed, with a given set of conditions, either the speed margin or the schedule

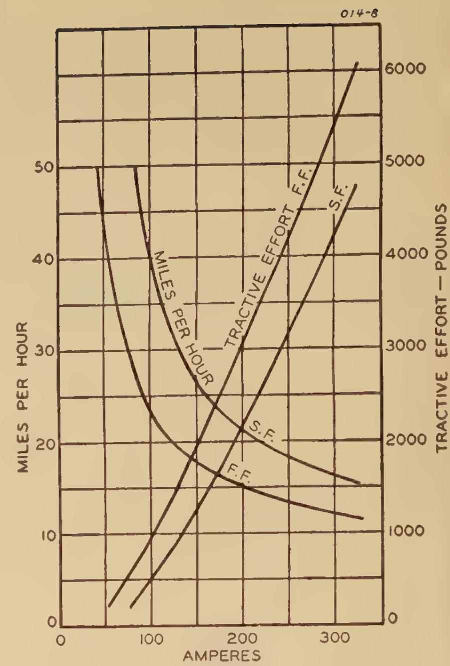


Figure 8. Trolley-coach motor B

Gear ratio, 10.61:1; wheel diameter, 40 inches; volts, 550

speed must be changed. Both cannot remain the same. Also it is incorrect to assume that changes of the character discussed will always result in the same percentage change, because while the same trend exists the amount of the change is dependent on the characteristics of the particular motor and other conditions.

Because the trolley coach retains some latitude in the selection of electrical equipment and gear ratio, it is selected to illustrate the method of application. The following basic conditions apply.

The coach weight with average passenger load is 23,000 pounds. The motor has a one-hour rating of 125 horsepower. The gear ratio is 10.61:1 (as extensively used). The effective rolling diameter of the tires is 40 inches. The average voltage is 550, which is typical. Train resistance increases as the speed of the vehicle increases but it varies so widely

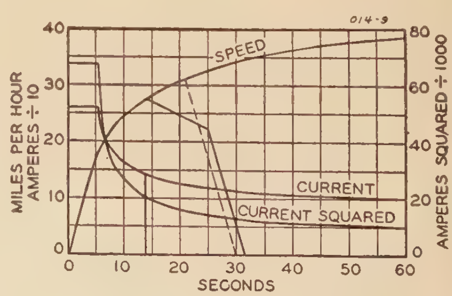


Figure 9. Trolley-coach performance curves

Motor *B*; average voltage, 550; gear ratio, 10.61:1; normal acceleration and braking

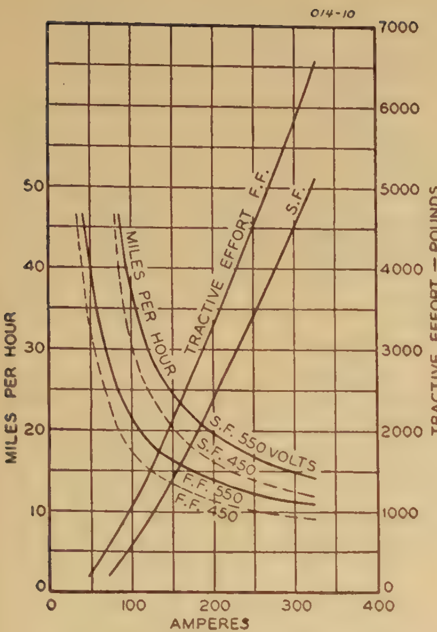


Figure 10. Trolley-coach motor B

Gear ratio, 11.42:1; wheel diameter, 40 inches; volts, 550

with type and condition of pavement that a constant value of 40 pounds per ton is used during motoring. This is amply high for the speeds normally reached. During coasting, the vehicle supplies the no-load losses of the axle and motor. The coasting resistance is thereby increased and a constant value of 47 pounds per ton is used. An average accelerating and braking rate of 3.5 miles per hour per second is used and is as high as can be employed consistently. The minimum time in which the equipment can travel a certain distance under these conditions is increased by a "speed margin" of five per cent (to allow for unavoidable interferences) and schedule speed, motor heating (root-mean-square current) and energy consumption are calculated on that basis.

Figure 1 shows the performance curve of motor *A* on full field and with two percentages of field shunting. The relatively small amount of shunting is designated F.S.-1 and the large amount F.S.-2. By using the motor characteristic, figure 1, and the accepted methods of calculation, the speed-time, current-time, and current squared-time curves are derived and plotted. Starting tractive effort is 4,490 pounds. Accelerating current is 346 amperes. The full-field motor curve is reached at 17.2 miles per hour and the S.F.-1 curve at 18.4 miles per hour. Five different runs between 0.076 mile and 0.369 mile are shown in figure 2.

The one-sixth-mile run may be taken as typical of average trolley-coach service. The required distance without coast is obtained in 29.1 seconds. Adding five per cent speed margin for the typical run with coast gives a running time of 30.56 seconds. The average duration of stop is taken as 7 seconds. Therefore, the total time for this run is 37.56 seconds and the schedule speed is 16.0 miles per hour. The heating current for the total time is 161 amperes which is within the capacity of the motor. The energy consumption is found to be 3.15 kilowatt-hours per coach mile at 550 volts.

The calculated coach performance for the range of runs indicated is shown in figure 3, plotted with stops per mile as abscissas. The decrease in schedule speed and the increases in energy consumption and heating current as the frequency of stops increases are evident. For example, an increase in stops per mile from six to ten decreases schedule speed 23 per cent, increases energy consumption 33 per cent, and heating current 7 per cent.

Field Shunting

The characteristic curve of motor *A*, figure 1, shows by curves F.S.-2 the performance of the motor with fields shunted much more than for F.S.-1. Equipments embodying this characteristic are operating in two cities where they have proved to be very popular with both operators and the public. Their principal advantage lies in maintaining a high rate of acceleration up to high coach speeds and thus enabling the trolley coach to hold a position of superiority where traffic moves unusually rapidly. On the other hand, equipments having the characteristics shown by F.S.-1 are in service in many cities and their performance on the street is entirely successful.

Figure 4 shows the calculated performance with F.S.-2. The full-field accelerating current is the same as for figure 2 but the shunted-field curve is reached at a speed of 25.6 miles per hour instead of 18.4 miles per hour as with F.S.-1. A speed of 30 miles per hour is reached in 10.2 seconds instead of 15.77 seconds. The resulting performance compares with that for F.S.-1 as follows:

Stops Per Mile		Schedule Speed (Miles Per Hour)	Energy Consumption (Kilowatt-Hours Per Coach Mile)	RMS Amperes
2	F.S.-1	24.6	1.84	136
	F.S.-2	28.8	2.21	175
6	F.S.-1	16.0	3.15	161
	F.S.-2	16.7	3.47	186
10	F.S.-1	12.3	4.19	172
	F.S.-2	12.5	4.25	181

Attention is called to the fact that the increased speed of the motor affects schedule speed, energy consumption, and root-mean-square amperes most in the infrequent-stop service and least in the frequent-stop service. The reason for

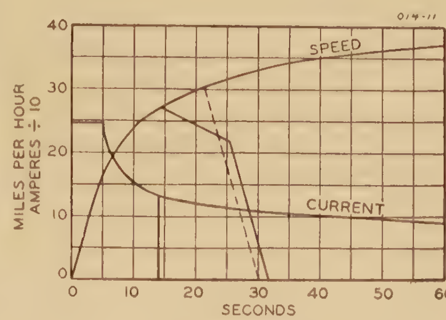


Figure 11. Average voltage, 550; normal acceleration and braking

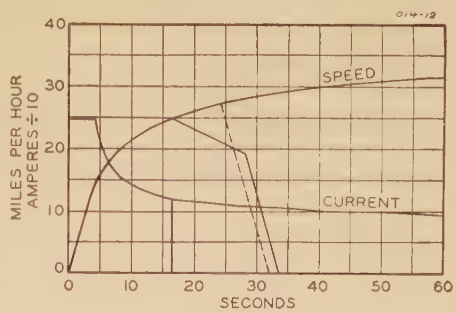


Figure 12. Average voltage, 450; normal acceleration and braking

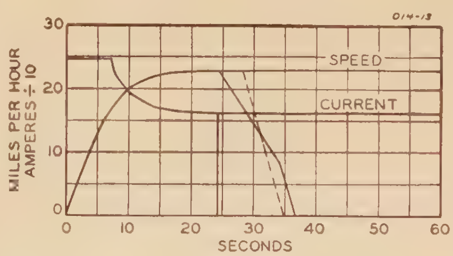


Figure 13. Average voltage, 550; normal acceleration and braking; up five per cent grade

Figures 11–13. Trolley-coach performance curves

Motor *B*; gear ratio, 11.42:1

this is the greater amount of operation on the shunted field curve as length of run increases.

Acceleration and Braking

Changes in rates of acceleration and braking affect performance. Taking exactly the same conditions as for figure 2, except rate of acceleration and braking, the performance on a one-sixth-mile

run has been calculated for the following combinations:

	Rate of Acceleration (Miles Per Hour Per Second)	Rate of Braking (Miles Per Hour Per Second)
Figure 5	2.5	3.5
Figure 6	3.5	2.5
Figure 7	2.5	2.5

Any decrease in rate of acceleration or braking obviously increases the time required for the run. A decrease in accelerating rate alone, as in figure 5, decreases the schedule speed almost five per cent. The accelerating current has been decreased from 346 to 274 amperes but the energy consumption is unchanged because the duration of constant current has been increased. If, instead of maintaining the same speed margin, an attempt were made to make the same schedule speed as in the original example the energy consumption would be increased.

A decrease in braking rate only, as in figure 6, again reduces the schedule speed five per cent. However, the energy consumption is reduced seven per cent. This results from retaining the economically high rate of acceleration and the covering of a greater portion of the distance during coasting and braking when power is not applied to the motors.

When both accelerating and braking rates are reduced as in figure 7, the schedule speed is reduced almost nine per cent and energy consumption is reduced only five per cent.

Slow-Speed Motors

The foregoing comparisons have been with one specific motor. The effect of using a motor with different characteristics, motor *B* of figure 8, will be considered now. This motor has a much slower full-field speed curve than motor *A* and a steep-shunted field curve. In the balancing-speed range the speeds are the same. The effect of the slower full-field curve is to increase the tractive effort per ampere. As a result the starting current is only 260 amperes, or 25 per cent less than the 346 amperes starting current of motor *A*. Figure 9 shows the curves for a one-sixth-mile run.

The schedule speed is 15.64 miles per hour; only 2.3 per cent less than with motor *A*. But heating current is reduced 20 per cent and energy consumption is 17 per cent less. In several cities, motors of both types *A* and *B* have been applied on the same type of vehicle. They have been able to maintain the same schedule speeds and the saving in energy consumption of motor *B* has been very close to that calculated.

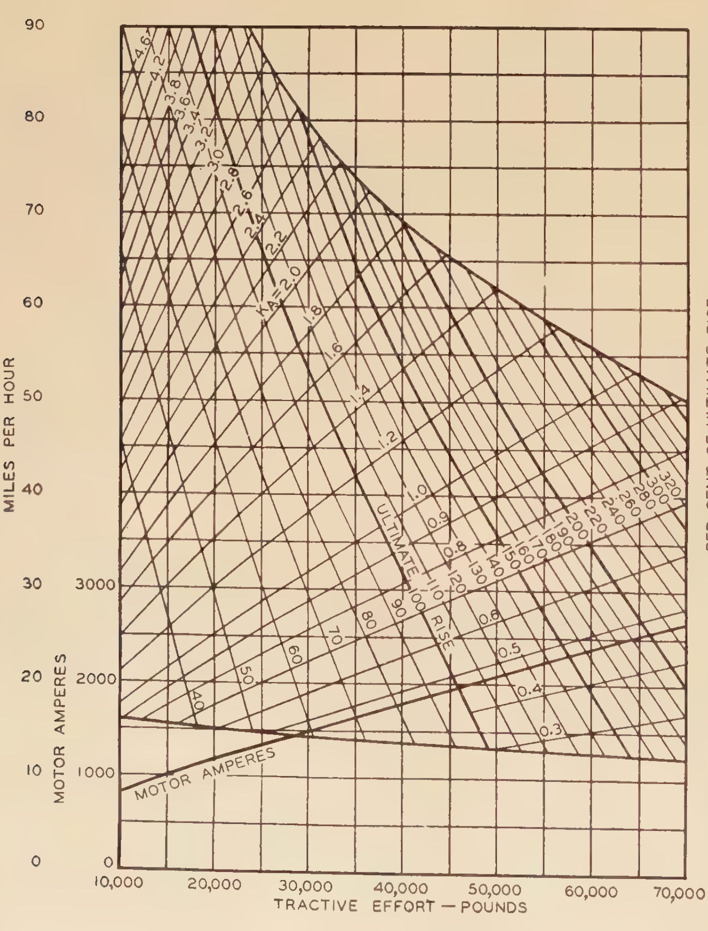
Gear Ratio

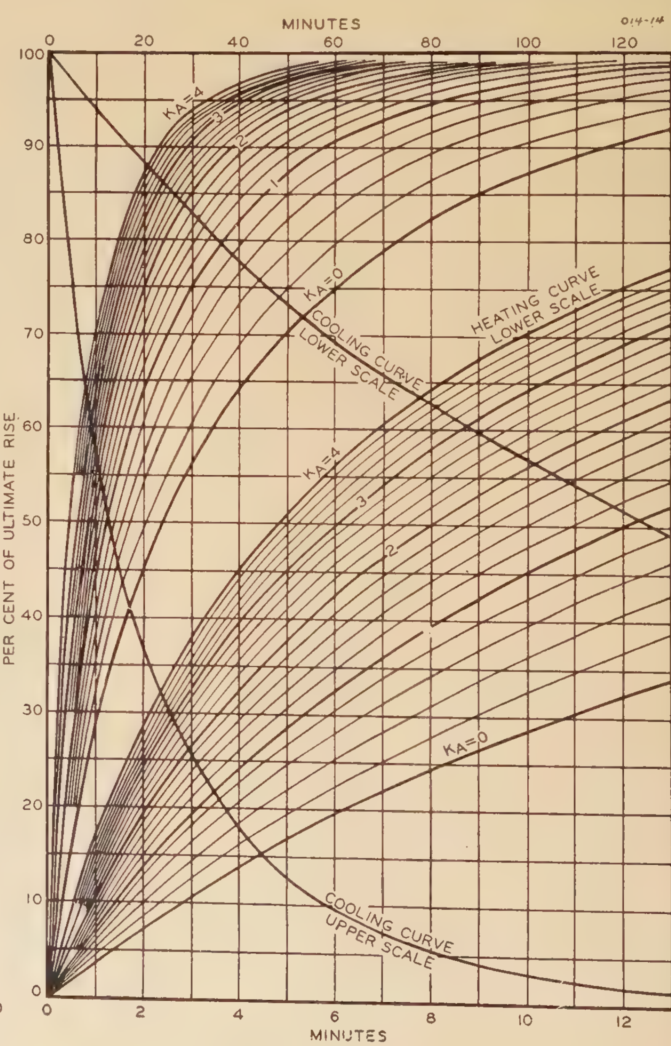
With less severe speed requirements it is possible to secure even more economical performance with motor *B* by using a gear reduction of 11.42:1. The motor curve for this gearing is shown by figure 10 and the curves for a one-sixth-mile run by figure 11. The accelerating current becomes 247 amperes, 29 per cent less than with motor *A*. Energy consumption is 20 per cent less but schedule speed is reduced only 3 per cent.

Voltage

Figure 12 shows the effect if the average voltage at the motor is reduced from

Figure 14. A-c series motor ultimate-temperature-rise and time-temperature curves





550 to 450 volts, all other conditions being the same as in figure 11. The schedule speed is reduced almost 5 per cent and energy consumption at the coach is reduced 15 per cent. However, low voltage is usually the result of drop in the distribution system, hence it is necessary to compute the energy delivered by the substation to obtain a true comparison. At 600 volts the values become 2.75 and 2.86 kilowatt-hours per coach mile for the conditions of figures 11 and 12 respectively. The reduction in energy at the car due to slower schedule is more than offset by the energy lost in distribution. Also in any particular service a definite schedule speed must be maintained. Low voltage reduces the amount of coasting and increases the energy consumption at the substation even more than calculated above on the basis of a fixed speed margin.

Grades

Few cities are entirely level. Obviously grades increase running time and energy consumption. When the profile of a line is rolling with its two ends at approximately the same elevation, it is customary to calculate performance on the basis of an equivalent grade resistance. The percentage of equivalent grade is calculated by adding all the rises in feet in a round trip, multiplying by 100, and dividing by twice the round-trip distance in feet.

Where there is a long grade in one direction and a material difference in elevation of the ends of the line it is necessary to calculate both an up-grade run and a down-grade run. Where there are short down grades at various points in a long continuous up grade it is customary to calculate the average percentage grade by adding the rises in feet, subtracting half the sum of the drops, multiplying by 100, and dividing by the length in feet. This formula, as well as that for equivalent grade, is based on the assumption that half of the potential energy in the vehicle at the top of any rise is recovered in useful work in descending the grade and that half is dissipated in the brakes.

On the usual hilly route the profile must be analyzed and divided into various equivalent-grade, up-grade, and down-grade sections. Separate calculations of performance are made for each section and the results combined on the basis of the lengths of the sections. In steam-railroad electrification and rapid-transit work, where the stopping points are definitely known continuous speed-time curves are frequently calculated and the effect of each condition of grade, curve, and speed restriction is taken into account. This process is rather laborious and is used only when the service cannot be represented properly by typical runs.

Figure 13 shows the performance of the same equipment as figure 11 under the same conditions except on a five per cent up grade and with accelerating current held at the same value as on the level. The accelerating rate, therefore, is reduced by the grade resistance of 100 pounds per ton to 2.5 miles per hour per second. Schedule speed is 12 per cent less but energy consumption is increased 75 per cent from 2.52 to 4.40 kilowatt-hours per coach mile.

Rapid Transit

In general, rapid-transit motor application follows the practice used for surface vehicles. In rapid transit, high-speed spring-supported motors with separate gear units have not yet been accepted generally, largely because rapid-transit equipment has always been applied on a very conservative basis. The reasons for this conservatism are (*a*) the seriousness of any failure which may cause a road delay in subways or on elevated structures, (*b*) the large number of cars usually involved in any extension of service, and (*c*) the requirement that new equipment must operate in train with existing equipment. However, in spite of these conditions there is a definite trend toward the use of lighter-weight higher-speed equipment.

Locomotives

The application of motors on locomotives differs from the application on cars or trolley coaches in some respects. The latter vehicles are seldom, if ever, subjected to runs of long duration with the motor tractive effort close to the slipping point of the wheels. Locomotives frequently start and pull trains for long distances under such conditions. Therefore, the locomotive motor must be able to commutate successfully the current required with good, sanded rail. Effort is made to apply electric-locomotive equipment so that the motors in the specified service will not be damaged by any conditions within the limits of adhesion between wheel and rail.

Heavy traction locomotives may run without stops for distances of 50 miles or more over a varied profile. The application of a-c series motors, used principally on such locomotives on electrified railroads, presents problems different from those encountered on d-c motors. The factors which produce heating of the motors are different. The heating of a d-c motor depends almost entirely on the current and ventilation. In addition, the heating on an a-c motor is greatly affected by speed; that is, the current rating increases with reduction in speed. As a result, motor heating depends on horsepower output rather than on current. Consequently, some method other than the calculation of root-mean-square current must be used to determine the heating of a-c series motors.

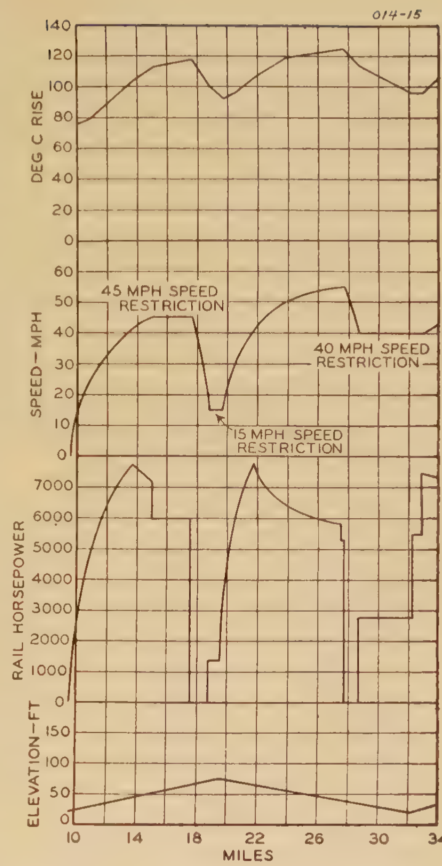


Figure 15. A-c locomotive. Profile, horsepower, speed, and temperature curves

A series of heating and cooling curves for the a-c motor over its entire operating range is determined by test. For each section of the profile the tractive effort and speed are calculated and, from the curves at the left of figure 14, the corresponding values of K_A and ultimate temperature rise are read. The number of minutes for the section is calculated from speed and distance. For this number of minutes the per cent of ultimate rise for the value of K_A is read from the curves at the right of figure 14. This percentage converted into degrees gives the temperature rise in the section. The cooling curve shows the per cent of initial temperature at the end of various durations of no-load operation. When

the calculations for a run are completed a continuous temperature-rise curve over that run is available. A typical section of such a curve is shown in figure 15.

Self-Propelled Vehicles

On self-propelled vehicles the electric generator and motor serve simply as a means of smoothly transmitting power from the engine, running at relatively constant speed, to the vehicle's driving wheels which run at speeds between zero and the maximum required. The problem is so to design the electric machines that minimum power is lost in transmission and that the engine is fully loaded over a wide range of operating conditions. In the case of locomotives or cars operating on long runs the electrical equipment in general must be capable of utilizing full engine power for long periods. In the case of busses in frequent stop service, full engine power is exerted only a small percentage of the time and electrical equipment capable of transmitting full engine power continuously would be uneconomically large and expensive.

Gear ratio has little effect on the schedule speed of a self-propelled bus with electric transmission in city service because the input to the electrical equipment is fixed. Therefore, with a specific engine output the tractive effort at any given vehicle speed within the normal operating range is the same regardless of gear ratio, except for the difference in efficiency resulting from different values of current and voltage. The greater the gear reduction with a specific equipment, the greater is the tractive effort at starting, but the lower is the vehicle speed at which the engine is not fully loaded by the generator and "runs against" the governor. Greater gear reductions result in lower current demand and hence lower temperature rise of electrical equipment.

Summary

The basic methods of calculating the service performance of traction motors have proved to be correct throughout years of application. In some installations, at first glance, results in service seem to contradict theoretical calculations. Careful analysis of such cases discloses that the service conditions or methods of operation differ from the basis of calculations. It has been seen that the calculations themselves are simple. To determine the correct basis requires experience and judgment.

To secure maximum economy of operation, the total operating costs must be studied for each application. Higher schedule speeds tend to reduce expense of vehicle operators but increase power costs. For each particular service it must be determined whether increased schedule speed will actually reduce the number of vehicles in service or merely increase wasted time at the ends of the route. On the other hand, it must be borne in mind that high schedule speeds have merchandising value and usually attract additional patronage.

The greatest power economy in city service is obtained by providing motors with the slowest practicable full-field speed and with a shunted-field speed which can meet the requirements of schedules with a speed margin of some five to ten per cent. The highest accelerating and braking rates practicable should be maintained. Vehicles and equipment of the lightest weight consistent with reliable operation and low maintenance should be employed.

In the future a greater degree of standardization may be expected. The continued use of electrical apparatus in transportation is dependent on obtaining the maximum economy both in first cost and operating cost. According to most recent data 8,000,000,000 kilowatt-hours are consumed annually by the electric railways. All electrical engineers should be interested in retaining and increasing this load for the electrical industry.

A New Postgraduate Course in Industry in High-Frequency Engineering

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THOSE FIELDS of engineering which utilize high-frequency electric currents and electronic devices have long ago graduated from the trial and error stage. The empirical experimenter who is ingenious and observant will always be useful, especially in some new and fruitful phase of the art not yet well understood. However, reliance has for many years been placed upon the ability of the engineer to design analytically upon a sound basis in the underlying theory and analytical tools are recognized as valuable aids and guides in laboratory work.

The newer fields of application in radio have made the engineer's need for a firm foundation in theory constantly more essential. Thus, the complication in both number and operation of the components of a television system is such that the ability to predesign results in untold savings. The problems of short waves have made clear to the engineer that many concepts in electricity he had regarded as basic are narrow in scope, limited to comparatively low frequencies, and inadequate if not altogether erroneous when applied to ultrahigh frequencies.

A major recent development in radio is a system combining frequency modulation with limiters. This outstanding improvement was due to a man who possessed intuition, vision, and courage. He is also a fine analyst in the broad sense of understanding exceptionally clearly what goes on in radio circuits. Success would not have been attained without the intuitive invention but it is doubtful if intuition alone could have solved the problem if the inventor had not had a very clear idea of the theory involved. Of course, after the whole problem had been solved technically, great vision and courage and determination were necessary to bring it to its present state of acceptance.

Even those workers who possess the highly inventive type of mind and are able to find new ideas with only a hazy notion of the theory behind their experiments can have their programs radically accelerated by the assistance of fellow workers who can correlate experiment with sound theory.

To push forward the understanding of high-frequency theory, and provide a solid foundation for good design and

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development requires that the engineer possess: (1) the analytical tools; (2) the ability to apply these tools to the solution of practical engineering problems. The latter characteristic includes more than simply the ability to substitute into a formula; it involves also the ability to extract out of a practical situation the problems whose solutions have bearing on the ultimate answers, the judgment to introduce the usually necessary approximations, and finally the important ability to express the results in an easily understandable and useful form.

Need for Course in Industry

Men rarely come to industry direct from college with the amount of training in the difficult radio field that is required for the possession of both of the foregoing characteristics. This is not stated in the nature of a criticism of college curricula. At least as far as undergraduate work is concerned, it is undoubtedly best to give basic and general training to engineers, leaving the study of more specialized branches of engineering to postgraduate work as is being done in many colleges.

Among the subjects of special interest to high-frequency workers but for which there is little time in an ordinary four-year course (and in many five-year courses), is the study of Maxwell's field equations. Unless time is devoted to a study of this theory in postgraduate work, even a phenomenon so fundamental to radio engineering as the radiation of energy by electromagnetic waves is seldom understood. Displacement current may be somewhat familiar to the student but the consequences of the concept are usually not appreciated until problems concerning it are met and solved. Without a feeling for retardation in electrical phenomena one is usually limited to concepts of inductance and capacitance which are valid only at low frequency. Even aside from retardation effects, it is necessary that the high-frequency engineer possess a broader notion of resistance, inductance, and capacity in which current distribution and proximity effects play a part, so that these circuit concepts are not thought of as necessarily independent of frequency. The ideas under discussion here are not new, but there is a need for more young men who thoroughly understand them.

Because it is necessary to teach circuits in a way that will be useful to students who may ultimately enter either the power or communication fields, circuit equations and concepts are most often introduced to the student as one branch of science he must master, and field theory (if treated at all) as another. When the frequency of the circuit is increased to the point that radiation of energy must be considered, the student without additional training is apt to find his circuit concepts inadequate in explaining the phenomenon. For ordinary circuits, he thinks of Kirchoff's and Ohm's laws; for radiation problems there has been little opportunity to equip him with more than a formula or two whose derivation he may not have seen, still less understood.

Transmission-line theory is usually presented entirely from the "voltage along the line" and "current along the line" standpoint. The notion of the transmission of electrical energy by means of propagating fields is so often passed over, or only mentioned as "an interesting way of looking at transmission," that when confronted with the problem of analyzing the transmission of power down the inside of a single hollow conducting tube "wave guide", the student has no basis for attack. Even if time has been found to treat the field concept in college and the graduate does possess a certain amount of appreciation for it, to set up the electromagnetic field equations and solve them in practical cases requires ordinarily more mathematical ability than the student has had a chance to acquire.

In acquainting the student with the operation of electron tubes, the "machinery" of the electronics or radio engineer, the available college time must be limited to the simpler problems. Thus this theory is usually taught in such a way that when higher frequencies are used and problems arise because of the presence of previously negligible transit-time effects, the student must discard what he thought were the basic concepts underlying amplifier or oscillator action and learn a set of more fundamental ones. For example, he can no longer assume that the number of electrons arriving per second at the anode of a diode is exactly equal at every instant to the number leaving the cathode; nor must he take as fundamental that a negatively biased electrode which collects no electrons does by that token not require any driving power.

Some students with more years of college study or an unusual selection of courses obtain a thorough background in the fundamentals of electricity and magnetism and the mathematical tools necessary to apply the theory. To these cases the examples cited are not applicable. However, it is again rare indeed that these men will have had the exposure to the practical type of problem in which the problems themselves are often difficult to isolate and the theory can be used only after a number of engineering approximations have been made.

In general, it may be said that there are three kinds of ability required in engineering work. Analytical ability, though essential, is not the only one demanded by industry. The highly inventive type of mind that contributes valuable ideas, often without apparent need for theoretical background, is one that is unfortunately too rare. The third type of ability, to follow directions and copy designs, also has its place. It is upon the first two kinds of ability, however, that we must depend for technical advancement.

Now, the ingenious inventor is difficult to recruit, for the colleges (especially in undergraduate years) have little time to detect this ability. The analytical man on the other hand is selected by his college record and examinations and trained with success. Since postgraduate study is essential to supply men for the more difficult phases of high frequency and electronics, and since the combination of analytical and experimental ability is so desirable in this field, it has seemed logical to equip men with analytical tools while actually engaged in practical work in industry. This work allows the man with inventive ability to strengthen it while engaged in experiment or design; against it as a background, the newly learned theory may become at once an active tool.

As John Dewey, the famous philosopher and educator has said:*

> "But there is all the difference in the world whether the acquisition of information is treated as an end in itself, or is made an integral portion of the training of thought. The assumption that information which has been accumulated apart from use in the recognition and solution of a problem may later on be freely employed at will by thought is quite false. The skill at the ready command of intelligence is the skill acquired with the aid of intelligence; the only information which, otherwise than by accident, can be put to logical use is that acquired in the course of thinking. Because their knowledge has been achieved in connection with the needs of specific situations, men of little book-learning are often able to put to effective use every ounce of knowledge they possess; while men of vast erudition are often swamped by the mere bulk of their learning, because memory, rather than thinking, has been operative in obtaining it."

This theory of education agrees with the experience of the General Electric Company.

* From his book "How We Think," pages 52 and 53.

Postcollege Training at the General Electric Company

The General Electric Company has had experience in fitting men with the essential qualifications implied above for work in electrical, mechanical, and thermal engineering. The three-year postgraduate course, known as the Advanced Course in Engineering,† has been in operation for about 16 years during which time it has graduated several hundred engineers. In view of the successful operation of the courses in other branches of engineering a new section of the advanced course has been organized to cover electronics and high frequency engineering. Before describing the new course it will be well to summarize briefly the aims and operation of the advanced course in general.

When the advanced course was instituted, the company realized that its achievement thus far had rested in a large measure upon the sound technical foundation laid by the pioneers and that future progress would depend on filling their places with high-caliber men who had the ability to think along fundamental lines, apply their knowledge to the development of improved apparatus, and deal generally with the advanced theoretical aspects of engineering work. It was recognized that such work is essentially mathematical in character and that in order to deal effectively with such problems one must be able to use mathematics as a tool in the application of fundamental laws of physics to the problems of engineering and must have a real appreciation of its significance as an aid in straight thinking.

Engineering graduates from American colleges, however, usually did not have sufficient training along the necessary lines. Most of them had no mathematical training beyond the calculus, and those who had studied differential equations had not learned how to make use of them in the analysis of physical problems. There were coming to the company relatively few engineers who were thoroughly grounded in methods of analysis. The courses in many colleges had become too practical; men were being taught routine rule-of-thumb methods of design, and there was insufficient emphasis on thinking problems through by the use of fundamental principles.

The experience of the founders of the course, R. E. Doherty and A. R. Stevenson, Jr., and of those with whom they were associated indicated very definitely that in order to be effective the course should have two major objects. These objects were to train men:

1. To apply the fundamental principles of engineering to the solution of their problems.

2. To present the results of their work clearly and concisely, whether in written form or orally, so that others might easily understand and use these results.

In the 16 years since its founding these objectives of the course have been adhered to.

The first year, or *A* class, is common to all sections of the course and is made up of 30 to 40 men of the testing department who have been with the company only a short time. Entrance is competitive and selection is made from among the applicants on the basis of an examination, school records, and personal interview. Personality and ability to co-operate with others are carefully considered, as well as technical ability.

Those selected remain in the testing department and obtain the same experience there as those not taking the course. In addition, they spend a half day a week in class on company time.

The work during the first year consists of a study of the application of the fundamentals of engineering to the solution of problems involving mechanics, thermodynamics, heat transfer, electricity, and magnetism. Throughout the three years of the course, as far as possible the problems selected are ones which have actually arisen in the engineering departments of the company. In many cases unsolved problems have been assigned, and the classes have thus been given the chance to be of assistance in useful engineering work. These problems differ from most textbook problems in that the students are expected to select from a group of facts those which are necessary for the solution. Another important aspect is that usually it is necessary for the students to make a number of simplifying assumptions in order to bring the problem within the range of practical mathematics. About 15 to 20 hours a week are spent at home by the students in solving and writing up their problems.

Lecture Material in the High-Frequency Section

A few of the 12 or 15 men selected each year from the *A* class for the upper classes are given the final two years of that part of the course dealing with electronics and high frequency. They leave the testing department and are taken directly on the payroll of the advanced course. While on this payroll the men continue to spend at least a half day a week in class on company time. The class work during the second and third year is illustrated by the accompanying chart giving briefly the work of the first year, and in more detail, the lectures of the second and third years.

This chart is intended to show how the mathematical, physical, and design material is developed simultaneously so that uppermost in the student's mind is the regard for the analytical processes as useful tools when properly applied in the solution of engineering problems. The subjects given in the table are intended to be merely illustrative and will change from year to year, although the fundamental nature of the lecture material is preserved. The material is adjusted to fit the needs of the company, the problems which arise, and the previous background of the students such as the *A* class. The technical lectures are given by a great many men from many different departments. In this way, the subjects are presented from many different points of view and there is little danger of the course becoming "inbred".

Problem Assignments in High-Frequency Section

The greatest part of the value of the course is obtained by the student in solving the weekly problems. Therefore, their variety and difficulty are a measure of the engineering ability that is both required and developed. For the purposes of discussion the types of problems assigned in the final two years of the course may be divided into several classes, although, with the exception of the first group discussed below, the problems will usually possess characteristics of two or more of the classes to be described.

The first class of problem is the academic type—given certain facts, to deduce certain relations, or prove other facts. This type of problem is one the student is used to solving from his college career. He finds the problem definite and knows that the answer can be found. Problems of this sort are assigned only occasionally as an exercise when a difficult and new concept is introduced; less than ten per cent of the assigned problems fall into this class.

A favorite type of problem, because of its frequent occurrence in practice and because it leads the student to fundamental thinking, is one that may be described as follows: An engineering design is to be attempted along conventional lines which are outlined to the student;

† "An Advanced Course in Engineering", A. R. Stevenson, Jr., and Alan Howard, Electrical Engineering (AIEE Transactions), March 1935.

Problems Encountered in Design	Theoretical Bases	Mathematical Tools
First year common to all sections		
	Mechanics	Differential equations
		Determinants
		Simultaneous linear equations
		Superposition
	Electricity and magnetism	Vector analysis
	Introduction to field theory	
	Elasticity	
	Waves and resonance	Fourier analysis
	Thermodynamics	Dimensional analysis
	Fluid flow	Functions of a complex variable
	Heat flow	
	Radiation	Operational methods
		Fourier integral
		Numerical integration
Second and third years in high-frequency section		
	Vibrating systems	Hamilton's principle and principle of least action
	Approximate methods for calculating resonant frequencies	LaGrange's equations
		Normal co-ordinates
	Hydrodynamics of sound	Review of vector analysis
	Equations of sound waves	Velocity potentials
	Reflection, absorption, attenuation, interference of waves	Solutions of wave equation
		Generalized curvilinear co-ordinates
	Radiation from various sound sources	Bessel functions
		Spherical harmonics
Horns	Physiological and psychological considerations in sound	
Loud speakers		
Microphones	Generalization of experimental laws of electricity and magnetism	
Sound measurement		
	Displacement current	
	Maxwell's equations	Scalar electric and vector magnetic potentials
	Static fields	Solutions of Laplace's and Poisson's equations
Electrostatic shields		Three-dimension flux plotting
	Varying fields in free space	
	Poynting's vector	Retarded potentials
Antennas	Electromagnetic radiation	Hertzian potential
	Electric waves in free space	
	Electric waves in ionized space	
	Electric waves over imperfect-conducting earth	
	Propagation characteristics of long and short waves	
	High-frequency resistance, inductance, and capacitance	
	Waves in and near conductors, guided waves	Solutions of "heat" or skin-effect equation
High-frequency shields	Maxwell's moving images	
Electrical measurements	Introduction to modern physics (radiation, spectra, thermionic emission, photoelectric effect, etc.)	
	Motion of electrons in electromagnetic fields	
Vacuum tubes	Space-charge theory, static and transit-time effects	
	Kinetic theory	
Gas-filled tubes	Conduction through gases	
Rectifiers	Noises in tubes	
	Coupled-circuit theory	
Amplifiers	Reactance theorems	
Feed-back circuits	Circuit theorems	
Oscillators	Four-terminal network theory	
	Introduction to synthesis methods	
	Conventional transmission line theory	
	Characteristics of amplitude, frequency, and phase-modulated waves	Series expansions with Bessel and other functions
Modulators and demodulators	Nonlinear circuits	
Radio transmitters	Distortion in tubes	
Radio receivers		
Applied optics	Geometrical optics	
	Physical optics	
Television devices	Electron optics	

however, because of certain unusual requirements it is feared that the usual type of design may not be satisfactory. For example, a connecting link is to be designed to operate between the antenna of a transmitter and the transmission line feeding it, and the student is acquainted with the usual type of design. In this case, however, the band width of frequencies to be passed is many times that which has ever been attempted with the common design. Should the design be altered or is it nevertheless satisfactory? Can an improved design more applicable to the wide band width be suggested? To deal with a problem of this type the student must ask such questions as: What constitutes a satisfactory connecting link? How does band width enter to determine the requirements of each part of the whole system and their matching? It would have been much easier for the student, had the problem been broken up into the finding of a frequency characteristic for each part of the system—a series of ordinary circuit or transmission-line analysis problems. Then, the student could have been given a series of rules determined by experienced designers by which he could ascertain whether the frequency characteristics indicate satisfactory or unsatisfactory design. But it is in the study of the bases for these rules that the student derives the training that will enable him to make original analyses in the future.

Many valuable problems come from the analyses of new inventions. Often an idea is suggested by analogy with a device in another branch of science or by certain physical considerations, and an analysis is required to determine whether the new idea is a workable one. In this case the student does not know beforehand whether the problem will require a long analytical study with many approximations, or whether the simple application of such tools as the conservation of energy and momentum or dimensional analysis may yield the necessary conclusion. One thing he is often certain of, however, is that the problem has not been solved before.

"When pupils get the notion that any field of study has been definitely surveyed, that knowledge about it is exhaustive and final, they may continue docile pupils, but they cease to be students."*

The largest group of problems are those in which an effect or characteristic is known to be present and the problem is that of obtaining quantitative data. These differ from the usual college problem in that in the first place many of them have never been solved before. The student does not have the assurance that by proper application of the material heard in the lecture the week before he is certain to obtain the result. The problem may not be exactly soluble. Almost always a number of approximations requiring a series of preliminary estimates have to be made. The student must decide whether to use a simple technique with additional computations intended to better the accuracy, or to approximate the problem by an exactly soluble mathematical counterpart for which a precise and elegant solution may be made.

Rotating Assignments

As was pointed out in the introduction, it is essential that the engineer (particularly in the high-frequency field) possess a balance in analytical and experimental

* From "How We Think" by John Dewey, pages 197 and 198.

ability, for one augments and enhances the other. To give this balance, during the second and third years of the course, the students are placed on assignment in various engineering departments of the company. Here they do regular engineering work varying from practice in standard design and manufacturing to research in the newest fields of radio. A good insight into the workings of a department is obtained during the assignment which may last for three or four months. (This period allows time for from six to eight assignments before completion of the course.)

Some of the assignments that the men in the high frequency section may have are as follows:

1. Design of radio and television transmitters and receivers.
2. Design of vacuum tubes.
3. Advanced development problems in radio and television.
4. Design and development of industrial control devices.
5. Design and development of gas-discharge devices of the power type.
6. Mathematical studies in the consulting departments.
7. Research in gas discharges, high-vacuum electronics, dielectrics, vibrations.
8. Research in electrical measurements.
9. District-office engineering, to obtain the customer's viewpoint.
10. Manufacture of radio receivers and vacuum tubes. A knowledge of factory processes and a real appreciation of the factors affecting cost are of prime interest to the radio engineer.

In these assignments, the men have proved so useful to departments in solving difficult problems and contributing new ideas, that the departments are glad to pay the men's salaries and often there are requests for students to fill assignments that must wait because of the limited number of students available.

Conclusions

Under this program, by the end of three years the men have received a thorough training in the fundamentals underlying electronics and high-frequency engineering. They have to a large degree learned how to use the analytical tools needed to apply the theory. It is comparatively easy for the graduate, when he is assigned to one particular phase of radio or television to go on by himself to master the special theory that applies. He is well acquainted with the problems and equipped to pursue their solution. Moreover he has obtained practical experience doing actual engineering work of varied types in regular departments alongside experienced men.

Discussion

H. W. Bibber (Ohio State University, Columbus): Stevenson and Ramo's paper will stimulate the thought of any teacher of electrical engineering who reads it with the problems of education in our field in the foreground of his mind.

To begin with, how is the student a few years out of college going to have the basic concepts in electricity which we gave him, widened in scope and extended to cover the ultrahigh frequencies which have now come on the scene? Here is a chance for the AIEE to help, by the publication in Electrical Engineering of educational articles specially written for this purpose.

Next, the authors statements as to what the industrial practice of high-frequency engineering requires is very reassuring to teachers who have been advising students who wished to enter this field, to take graduate work with particular emphasis on mathematics and advanced physics. Only a small proportion of students interested in this field can hope to secure employment with a company that has a training course like the one described in this paper.

The quotation from John Dewey serves to remind college teachers of the necessity of continuing some organized laboratory work at the graduate level, in order that use may be made of principles set forth in lectures or in books, "in the recognition and solution of a problem". It is fortunate that high-frequency phenomena may be studied with laboratory equipment that is not beyond the means of the larger colleges to buy or build from parts. The same cannot be said of the study of power systems or large machinery. Postgraduate study while employed in industry has so many advantages that it is only fair to mention one which college postgraduate instruction possesses. That is the easy availability of laboratory facilities to students to settle immediately minor points that may arise in the solution of a major problem. If a student runs into a question of whether an assumption or simplification is justified during an evening's work on a long problem, he may try it out the next morning with a minimum of red tape in securing permission.

It is true that colleges tend to organize and co-ordinate their instruction with assigned problems in courses in order to give a student in a few months a knowledge of principles which it took earlier pioneers in the field many years to learn from haphazard experience. But they do recognize that at an advanced level it is essential for a student to work on problems of an original character, whether he has already mastered the theory necessary to their solution or not. The master's thesis and the doctor of philosophy dissertation are the academic answer to this necessity. A fair share of a graduate student's time is usually devoted to such work, and the award of an advanced degree is usually based on satisfactory demonstration of ability to think independently.

In speaking of ingenuity, the authors state that the colleges (especially in the undergraduate years) *have little time* to detect this ability, and in many other places throughout the paper there is either direct reference to the lack of time and crowding of the curriculum or inferences to the same effect. To speak of the area I know best, I must agree that the curriculum in the great state universities needs lengthening in time with only minor additions to content. If the pressure on our students could be relieved in part they might be encouraged to show inventiveness in their regular course work, or outside of it. They would have time to make use of shop privileges for constructing devices, privileges that I believe are widely offered but little used.

The extension of the curriculum to five years in the state universities should be just a reduction of the credit units per semester, and not a preliminary year (or two years!) of arts work before coming to engineering.

The authors properly place much stress on analysis as one of the desirable qualities to be sought for and developed in students. The counterpart of this quality they mention as "inventiveness," without stressing an educational point which I believe is important precisely in connection with high-frequency work. It is suggested by the item in their list of "theoretical bases" of course content entitled "Introduction to synthesis methods", which is probably intended to apply to synthesis of networks. Most teachers would agree that synthesis should have a far larger place in the scheme of engineering education than it does. It is certainly the fundamental psychological process involved in designing new equipment. Some training in it seems to come as a reflex from training in analysis, and in the machinery field it is difficult to carry out. Thus it would be impracticable to have each student make and put together the laminations, windings, shaft, and frame of a particular motor that he had designed.

But in the high-frequency field, laboratory work intended to develop synthesis is far more practicable. Electron tubes can be built by students themselves within a wide range of dimensions, and circuits built up from a stock of parts which are luckily not so expensive as to prevent a college laboratory from having enough on hand to supply its graduate students. It seems to me that it is in high-frequency work in colleges that synthesis as an intellectual process in electrical engineering may be taught to the extent that it can be taught at all.

A perusal of this paper serves to emphasize the enviable situation of students who secure employment with a big company that can afford to operate a training course —and has the vision to see its value to its future operations—such as that described. For those recent graduates employed in metropolitan districts, the evening courses at the graduate level recently started by some colleges, such as those in the New York City region, may serve as a partial substitute.

Ernst Weber (Polytechnic Institute of Brooklyn, Brooklyn, N. Y.): As the authors point out properly, the average four-year college program in electrical engineering cannot find time for "fundamental" courses, that is, courses which develop the prerequisite mathematical and physical concepts in a rigorous manner and show their applica-

Table I

Mathematical Tools	Basic Theory	Applications
Vector analysis (*M*)	Maxwell's field theory (*M*)	Power transmission and distribution
Functions of a complex variable (*M*)	Operational circuit analysis (*M*)	Advanced electrical machinery
Advanced differential equations (*D*)	Fundamentals of mechanics (*D*)	Network analysis
Higher mathematical analysis I	Fundamentals of radiation	Network synthesis
Matrix and tensor analysis	Fundamentals of electronics	Electronic tubes and circuits
	Statistical mechanics (*D*)	Higher mathematical analysis II
	Quantum mechanics	

tion in practical problems. One might perhaps refer to the usual undergraduate program as a first "sightseeing tour" to be followed in the postgraduate programs by real "exploration". In this sense, the outline offered by the authors is an excellent contribution from the point of view of industrial training courses and comes very close to our own graduate program except that we spend more time on the individual phases and use considerably more rigor in keeping with formal academic training. Thus, our program for the advanced degrees comprises essentially the individual courses listed in table I of this discussion and grouped in a manner similar to the authors' listing of topics, though not necessarily implying a definite sequence. The courses required of all students for the master's degree are marked (*M*), and those required additionally of all students for the doctor's degree are marked (*D*). For specialization in the field of power or communication engineering a sufficient choice of selective courses is available, including courses in other fields not listed in table I.

The similarity between the fundamental first year of the General Electric course and our required courses is striking, as is also the parallelism of the two years in the high-frequency section of General Electric and our own elective list for students specializing in communication engineering. This need not surprise one in view of the fact that most of our evening graduate students come from the research and development laboratories of the industrial and manufacturing companies of the metropolitan area of New York and, therefore, represent just as selected a group of interested and progressive young men as are admitted to the General Electric training-course program. In fact, our students usually bring with them a rich store of individual experience which makes teaching an enjoyable and gratifying activity. Again, as the authors point out, the success of such a fundamental program depends primarily upon the spirit in which it is carried on and that in turn has very much to do with the teachers of the courses. The great advantage of an industrial training program is the availability of nationally known experts in the particular subjects of study, but there is no reason why the same should not be true for the advanced courses in a well-organized graduate school. More and more emphasis is now given to the appointment of experts to teaching positions in the graduate divisions and to encouragement of industrial contact of teachers by means of conferences, of summer work, and of subsidized research. This is particularly true for our graduate division to which we also were able to attract eminent part time faculty members from the metropolitan industrial concerns. Thus, the old criticism that school training is dry and impractical can no longer be maintained with respect to a graduate program of the kind indicated above.

E. A. Guillemin (Massachusetts Institute of Technology, Cambridge, Mass.): The basic ideas set forth in the paper by Messrs. Stevenson and Ramo with regard to postgraduate work at the General Electric Company are unquestionably sound. They apply equally well, however, to the undergraduate curriculum where in fact it is essential to instill in the students' minds ideas which, even though they are elementary, are entirely consistent with the fundamental principles of electromagnetic theory to be developed later. It was this thought which motivated the rather comprehensive revision of the basic undergraduate curriculum for the electrical-engineering department of the Massachusetts Institute of Technology begun some nine years ago. The undergraduate work cannot be as comprehensive as the usual undergraduate plus graduate study, of course, but there is no reason why, by proper selection of material and form of presentation, the undergraduate work cannot provide a background which is thoroughly sound with regard to fundamental principles so that these need only to be amplified, and not discarded for lack of soundness, when the student proceeds to build upon them in his graduate study, whether this is done in college or carried on in connection with his practical work in industry. The very fact that the industry finds it necessary to give a graduate course of this nature indicates that the need for doing something of this sort in the undergraduate curricula (and perhaps in some graduate curricula) is not generally recognized.

As a specific example let us consider a semiqualitative discussion of the relation between field theory and circuit theory. One naturally cannot expect a sophomore to fully master the mathematical mechanism necessary for a complete discussion of this rather complex problem. On the other hand, it is entirely possible and appropriate to forewarn the student that the lumped circuit parameters (*R*, *L*, and *C*) as calculated by the ordinary engineering methods are merely approximations which are adequate for the lower-frequency ranges. Qualitative reasons for this can readily be given; it is even possible to derive rough criteria which show when and why the simple methods may be expected to fail. Even if this first presentation is not properly digested by the student, he has at least acquired an open mind on the question and need not suffer disillusionment later on in finding things to be only half true which he had always been led to understand were the whole and unshakable truth.

It is another principle in our scheme of undergraduate instruction that when a conception is sufficiently fundamental, though admittedly difficult to assimilate, a certain percentage can eventually be made to "stick" if brought to the student's attention in small doses at sufficiently frequent intervals. In our opinion it is definitely unsound to maintain that certain so-called "advanced" concepts are inappropriate for undergraduate instruction. A course of action based upon such a premise makes the shock fatal when the time comes to tell the truth.

Here at MIT, after a certain background for the relation between electromagnetic field theory and circuit theory has been laid in the sophomore work, the student is conditioned to a certain degree to receive a more substantial dose in a subject dealing with transmission line theory which is given to the seniors in the communications option. This subject is introduced by an elementary discussion of electromagnetic wave propagation—plane waves in free space, conductors, or semiconductors, surface waves and the accompanying phenomenon of skin effect. The theory of the radiating dipole and its application to antenna problems, which forms the concluding material in this subject, follows also quite logically from the same introductory discussion.

It is fully realized that only a few of the abler students get more than a moderate grasp of the more advanced portions of such a discussion. We have no illusions on this score. But we do feel that attempts of this nature are worth the time and effort. For if some of the men do continue in this field in their graduate work it will then be a third exposure for them and they should be in a position to accomplish something worthwhile, whereas a serious treatment of fundamental electromagnetic theory will still be just a play of symbols to them if it is their first exposure.

There is, of course, a certain amount of good judgment in postponing the presentation of material of a more special nature until the graduate year because of the fact that the average graduate class is a more select group of students from the standpoint both of ability and serious interest. However, it is also possible to inject into the undergraduate teaching procedure the necessary flexibility to make available to the student a variety of opportunities to suit the individual or group interests and abilities. The procedure of sectionalizing according to mental speed, the individual encouragement given the more able students, and the operation of the honors group system are methods which have proved useful toward making possible the differentiation in subject matter and in teaching procedure necessary for effectively carrying out a more ambitious program.

The comprehensive written and oral examinations given the honors group men in place of the ordinary term examinations provide original problems of a comprehensive nature (contributed by practicing engineers) requiring for their solution the initiative and perspective which Messrs. Stevenson and Ramo point out as being essential to the proper training of student engineers.

Finally I would like to state the opinion that graduate courses in the industry ex-

cepting those peculiar to a particular industry are fine for those students who cannot afford such study in college, but since this type of work is a side line for the industry it should follow that the college, whose primary responsibility is teaching, can do a better job of it. On the other hand it is clear that efforts of this sort on the part of the industry are bound to have beneficial effects, not only within their own group but also in academic circles because such activity cannot but stimulate thoughts along these lines by men having teaching responsibilities and thus lead them to make more constructive appraisals of their own efforts.

C. Francis Harding (Purdue University, Lafayette, Ind.): Although possibly directed more effectively to the selection of personnel for such an advanced course than to the content thereof, I would like to ask what credit and advancement are available in such a program for those who have secured their master of science or doctor of philosophy degrees in the graduate schools of universities and colleges? Although it has been stated that such courses in industry are not in competition with similar graduate courses in the universities, yet unless advanced students entering industry can capitalize upon such university graduate training the competition does really exist and the time is actually lengthened during which the new employee must remain in training before he is able to carry responsibility.

The five-year courses which are being considered at various universities and the relation of their resultant product to the regular four-year curriculum, plus a year's graduate course in industry, have been presented. The necessity for more time for assimilation of the curriculum and for thesis or other original work on the part of the undergraduate student has been emphasized. It may be of interest to note that Purdue University has just established two new five-year curricula in engineering to meet such needs. Curriculum *B* is identical in content, and in the bachelor of science degree granted, with the present curriculum *A* except that it is spread out over five years. Curriculum *C* contains approximately 24 credit hours of nontechnical subjects with the specification that there shall be included therein a minimum of three extra hours of economics, six hours of history and/or government, and six hours each of advanced mathematics and physics. The remainder of the extra credit hours are expected to include more of the humanities, English literature, and social sciences. The same bachelor of science degree is granted with certificated recognition of the extra work which has been accomplished. The minors of a master of science degree may also be satisfied in such a curriculum if the subjects are selected with proper care and approval.

These curricula should not be considered as replacing, in any sense, the present standard four-year engineering curricula. They are made available as substitutes for those interested in devoting more time to the securing of the bachelor of science degree or for those who wish to secure a broader cultural background for such a degree. They are not expected to decrease the interest in, nor the election of, the requirements for the more rigorous curricula leading to the master of science degree.

R. W. Sorensen (California Institute of Technology, Pasadena): If I were to apply the common critical methods of my occupation to this paper, I would begin by changing the title to the extent of eliminating the word "new", thus having the title read: "A Postgraduate Course in Industry in High-Frequency Engineering". I do this, because I am not acquainted with any other postgraduate course in high-frequency engineering and I would like to give full credit to the authors for their original, efficient, and complete way of laying the proper groundwork or foundation for a particular engineering activity incident to the work being done by the company by which the authors are employed. When many of us were young men just out of college, our training courses with industry were quite different. We took our place in the shop with the workmen and organized our own theoretical classes or seminars, if any.

As a college teacher, I am more than gratified to note the continued introduction of special advanced courses by industry to meet the needs which arise, particularly as these courses are of a type that not only supplements the work done by technical men in college, but continues to develop in these men, in parallel with their supplementary practical work, an interest and a facility in the theoretical and analytical aspects of the work they are doing.

The course under discussion is such that it could well be a regular graduate course given in an engineering college, and therein lies one danger which should be avoided. That is, I think colleges should not give courses of the type described, not because of lack of quality or trend of such courses, but rather because such courses are too specialized for a general course and hence are too specialized for college courses.

In fact, one of the authors of this paper and builders of the course described in the paper is a young man recently out of college who did not have such a course as a part of his college curriculum. Nevertheless, he has been able to plan and teach the course here outlined. He could do this, because he obtained a doctorate degree for the completion of a graduate course in electrical engineering, a considerable part of which comprised advanced courses in physics and mathematics, taught by the ablest of teachers and research men specializing in these subjects, rather than by engineers somewhat versed in mathematics and modern physics. Even as an undergraduate, the college course which the author had, provided some tools for doing work of the type described in this paper. As the use of one tool was mastered by Doctor Ramo other subjects listed as tools in this paper were added, very much in the order named, as his work continued throughout the graduate course.

In fact, about the only contribution which I see can be made to the paper by my discussion is to show that the course described is sound, because it provides the men taking the course with technical ability which will enable them to make analyses which keep pace with the developments that take place in this field in laboratory and shop. Also, it provides for a continuation of theoretical and analytical study by men who have been properly prepared for such work and thus further knits together our whole program of education in college and industry through a co-operative rather than a competitive program.

As long as colleges confine graduate work to equipping men with analytical tools rather than endeavoring to do things which naturally pertain to industry, in the way of developing designers, etc., and do not make graduate courses merely continuations of undergraduate work—just so long will our whole educational program be an efficient, co-operative one between the colleges on one side and industries on the other.

A. R. Stevenson, Jr., and **Simon Ramo:** It is reassuring to the authors to find their colleagues in the colleges, who are specialists in the field of engineering education, in general agreement as to the advisability of training along broad, fundamental lines in preparation for engineering work in high frequency and electronics.

The question has been raised as to what credit and advancement are available to students with advanced degrees in a program such as we have described. To answer this, it should first be pointed out that there is no "standardization" in the placing and developing of men in the General Electric Company. This applies also to the placing and training of men in our advanced course. Each man is considered as an individual case. We have had some doctors of philosophy whose ability and training were sufficiently removed from that which we try to develop in the course that they were not able to complete the work of the first year. Others have been given only one or two years of the three-year course and some have been given the job of supervising a year of the course which they did not take.

We like to have men with advanced training in our classes both as students and lecturers. We depend upon these men who come to us with new tools learned under skilled professors to add to our course ideas of which we might not otherwise be aware.

It has been stated in discussion that co-operation between industry and the colleges makes for the most efficient educational program. From our standpoint, this statement has already been borne out well by the discussions presented by the teaching profession; many ideas were put forth which will help us to improve our educational system and make the best use of the collegiate training of the student engineer.

Condensation of Mercury in Mercury-Arc Tubes

JOSEPH SLEPIAN
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Synopsis: It is found experimentally that the efficiency of condensation of mercury vapor on cold metal surfaces is quite low. The condensing efficiency of steel surfaces is increased several fold by positive-ion bombardment of the surface. Nickel surfaces condense mercury vapor several times as efficiently as steel. The operation of a high-voltage ignitron rectifier was greatly improved by positive-ion bombardment of the condensing surfaces.

IN mercury-arc power converting tubes, there is a continuous evolution of vapor from the mercury-pool cathode. This vapor is recondensed upon condensing surfaces which are kept cool by water, in larger tubes, and forced or natural circulation of air, in smaller tubes. The vapor density existing in a tube will then depend on the dynamic balance between the evolution at the cathode, and the removal of vapor by condensation at the condensing surfaces. It is well known that the successful operation of mercury-arc tubes is strongly dependent upon the vapor density being kept low, at least in the neighborhood of the anodes. If the temperature of the condensing surfaces is allowed to exceed 60 degrees centigrade, operation usually becomes unsatisfactory due to excessive frequency of arc back.

In estimating the vapor density which might exist in mercury-arc tubes, the authors, and probably also mercury-arc tube engineers generally, had not been seriously concerned about a possible low efficiency for condensation on the condensing surfaces. Elementary mechanical considerations lead them to believe that heavy mercury atoms, striking a surface made up of atoms not heavier than mercury atoms, should lose all their kinetic energy with no recoil, and come to rest on the surface. Thus, all mercury atoms reaching the surface should be condensed, with no direct reflection, and mercury atoms should leave the surface again only as re-evaporation. Because of the low temperature of the condensing surfaces, this re-evaporation is generally negligible.

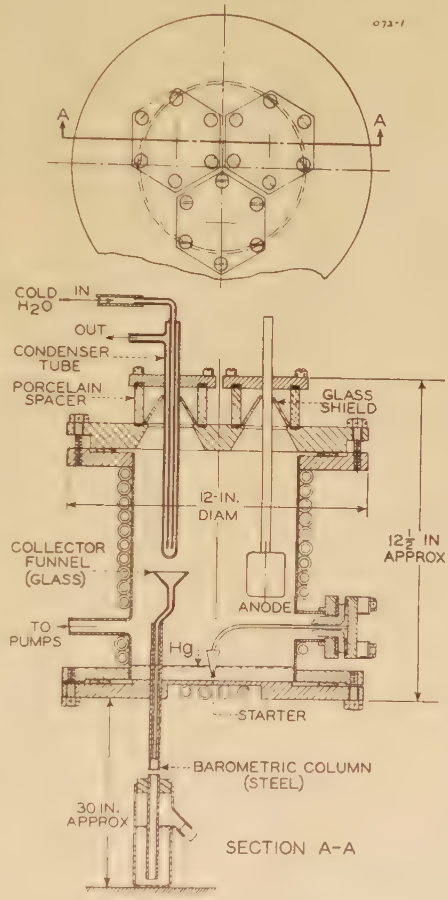

Figure 1. Mercury-condensation chamber

In estimating vapor densities, therefore, the authors never took into account a possible counterflow of molecules from the condensing surfaces, and it seemed that condensing surfaces generally used were sufficient to ensure a low vapor density at the anodes of tubes in operation.

It was a considerable shock, therefore, when Doctor R. C. Mason[1] called their attention to the fact that only for extremely clean condensing surfaces is the direct reflection of mercury atoms negligible, and that slight contamination, quite unavoidable in practical tubes, would reduce the condensing efficiency to very low values. This phenomenon has been known a long time to physicists,[2] but its significance seems not to have been appreciated by engineers.

It seemed desirable then to make a direct study of the efficiency of condensation of mercury on various surfaces under conditions similar to those existing in practical operating mercury-arc steel tanks. Also, it was desired to check the idea that continuous positive-ion bombardment might keep condensing surfaces sufficiently free from contamination that their condensing efficiency might be kept high.

Apparatus

The apparatus in figure 1 was built around an experimental ignitron tank as a foundation. The coils which are soldered to the sides and bottom of the tank were connected so as to form a closed circulating system with a water pump, electric water heater, and a thermostat. Thus, the temperature of the mercury in the bottom of the tank was known to the accuracy of the operation of the thermostat, which was plus or minus one-half degree centigrade. The special top plate, with provisions for three small electrodes was made for this experiment. The three electrodes were insulated from the rest of the apparatus by the porcelain spacers; the bolts which held them in place were insulated from the electrodes by Micarta bushings. Two of the electrodes were of the shape and size of the one shown on the left, while the third was an "anode," as shown on the right. Glass funnels under each of the two similar electrodes conducted the mercury which condensed on to and fell from the condensing tubes to the two barometric columns. Mercury so collected was drained from the barometric columns and weighed at suitable intervals. Readings taken in this manner had no effect on the conditions within the chamber. The third electrode, as shown, was used as an anode when it was desired to run an arc in the chamber, simulating conditions in an ignitron. Tap water was used to cool the condensing tubes. Seasonal fluctuation caused the temperature of the tap water to vary between 10 and 25 degrees centigrade. The vapor pressure of mercury in equilibrium with condensed mercury in this temperature range is low in comparison with that at 60 degrees centigrade, as the pressure doubles for each 10-degree rise in temperature in this range.

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JOSEPH SLEPIAN is associate director of research of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; W. M. BRUBAKER is with the same company.

1. For all numbered references, see list at end of paper.

Calculation of Efficiency From Observed Condensation

Besides directly investigating the relative yields of condensed mercury from various surfaces under different conditions, it is desirable to make an estimate of the efficiency, or condensation, coefficient. This coefficient may be defined as the number of molecules condensing divided by the number of molecules striking the surface. If the area under consideration is a condensing surface of extremely poor efficiency, so that there is no appreciable flow, a formula from simple kinetic theory may be used to compute the number of molecules which strike the surface per second. At the other extreme, a surface of 100 per cent condensing efficiency appears to the condensing vapor as a hole into a completely evacuated chamber. In this case, the vapor at the condensing surface is in a state of flow, and its density and temperature are different from that of the vapor at rest far from the surface. We may calculate what this flow will be by using the mathematical theory of the mechanics of continuous fluids, although we must recognize that at the condensing surface this theory fails to be applicable, since the vapor there, with its non-Maxwellian distribution of molecular velocities, cannot be said to have a scalar pressure and temperature as contemplated in fluid mechanical theory. However, this theory should be applicable up to within a few molecular mean free paths from the surface. We may then attempt to modify the simple kinetic-theory formula, by taking into account the flow and the altered density and temperature predicted by the continuous-fluid mechanical theory.

Kinetic theory gives v the number of molecules crossing from one side to the other side of a unit surface in unit time in a gas in equilibrium as

$$v = {}^1/_4 N\bar{c}$$

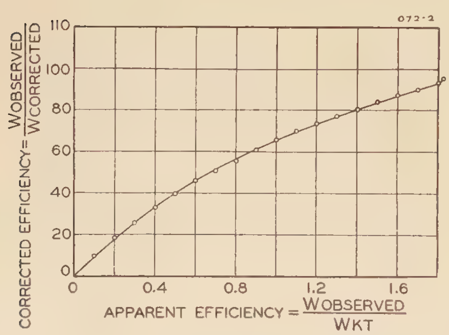

Figure 2. Calculated efficiency as function of observed yield

where N is the number of molecules per unit volume, and $\bar{c}$ is the mean velocity of thermal motion. The weight in grams of these molecules is

$$W_{kT} = p\sqrt{\frac{M}{2\pi RT}} = 43.7\times10^{-6} p\sqrt{\frac{M}{T}} \qquad (1)$$

where p is the pressure, dynes per square centimeter, M the molecular weight, T the absolute temperature in degrees Kelvin, R the gas constant in ergs per degree, and the units of area and time are the square centimeter and second.

From the mechanics of continuous fluids the mass of a perfect gas flowing per second across an area of one square centimeter at a point where the density is ρ grams per cubic centimeter, and the pressure p dynes per square centimeter is

$$W_H = \sqrt{\frac{2\gamma}{\gamma-1} p_0\rho_0\{x^2 - x^{\gamma+1}\}} \qquad (2)$$

where p_0, ρ_0 are pressure and density at a point where the fluid is at rest, γ is the ratio of specific heats and

$$x = \rho/\rho_0$$

Experimentally, W_{observed}, the observed rate of condensation per square centimeter is measured. Obviously, near the condensing surface

$$W_{\text{obs}} = V\rho = Vx\rho_0 \qquad (3)$$

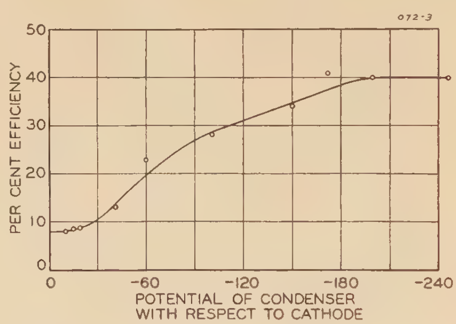

Figure 3. Effect on condensation of voltage applied to condenser

where V=mean or hydrodynamical velocity of motion of the gas toward the condensing surface. Assume that the molecules of the gas have a Maxwellian distribution of velocities about a set of axes moving toward the surface with the velocity V, although as mentioned before, this cannot be true within a mean free path of the condensing surface. From equations 2 and 3, we calculate V and x. We then return to (1) and modify it to obtain an expression for the number of molecules striking the surface in terms of the pressure and temperature of the vapor in regions unaffected by the condensation, and where it is at rest, taking into account the effect of the hydromechanical motion corresponding to the observed rate of condensation. Equation 1 is derived by integrating

$$\rho\int_0^\infty uf(u)du$$

where $f(u)$ is the Maxwellian distribution function for the velocities in a direction perpendicular to the area. If the body of the gas or vapor is approaching the surface with a velocity V, the distribution function will be $f(u-V)$. As we are

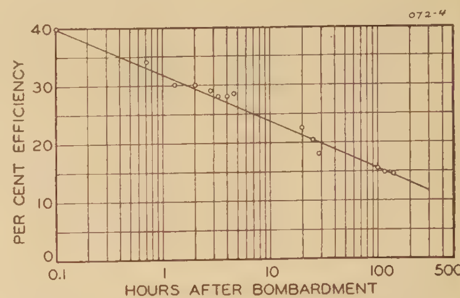

Figure 4. Decrease of condensing efficiency with time after bombardment

interested in knowing how these conditions deviate from those in our first equation, we let

$$R = \frac{\int_0^\infty uf(u-V)du}{\int_0^\infty uf(u)du}$$

$$= e^{-\left(\frac{V}{\alpha}\right)^2} + \sqrt{\pi}\frac{V}{\alpha}\left[1+P\left(\frac{V}{\alpha}\right)\right]$$

where $P(y)$ is the probability integral

$$P(y) = \frac{2}{\sqrt{\pi}}\int_0^y e^{-v^2}dy$$

and α is the most probable molecular velocity. Thus, equation 1 should be multiplied by R to allow for the motion of the vapor toward the condensing surface.

As the gas moves toward the condensing surface, it undergoes an adiabatic expansion. The changes in p and T from the equation of state of a perfect gas are given by

$$x = \frac{\rho}{\rho_0} = \left(\frac{p}{p_0}\right)^{\frac{1}{\gamma}} = \left(\frac{T}{T_0}\right)^{\frac{1}{\gamma-1}}$$

where γ is the ratio of the specific heats which for mercury vapor is 1.66. Hence, equation 1 will need to be modified to allow for this changed density and temperature by multiplying by $x^{\frac{\gamma+1}{2}}$. The

value of α in the correcting factor R, is also a function of x.

Combining all of these correcting factors, we obtain for calculated mass of molecules striking a centimeter square of area of condenser per second,

$$W_{\text{corrected}} = W_{kT}x\frac{\gamma+1}{2}R$$

$$= A(M, p_0, T_0, \rho_0, \alpha_0)F(W_{\text{obs}}) \qquad (4)$$

where A is a function of the conditions

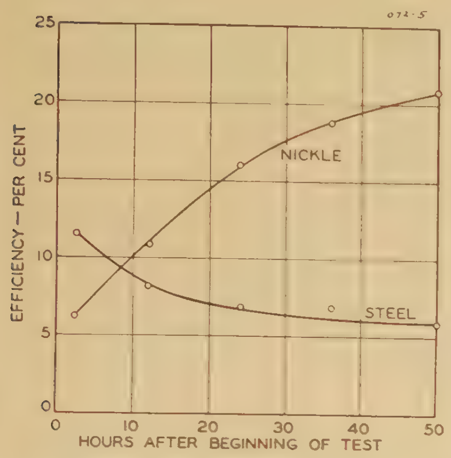

Figure 5. Efficiencies of condensers during a test

existing in the vapor at parts unaffected by the presence of the condensing surface.

The corrected efficiency $W_{\text{observed}} \div W_{\text{corrected}}$, can then be calculated from the apparent efficiency, $W_{\text{observed}}/W_{kT}$. A curve of corrected efficiency is plotted against apparent efficiency in figure 2. The data in this paper are expressed in terms of the corrected efficiencies as taken from figure 2.

Experimental Results

With the temperature of the condensed mercury 60 degrees, and that of the condensing surfaces 10 to 25 degrees centigrade, the efficiency of condensation of mercury vapor on freshly sand-blasted steel electrodes is found to vary between 1.5 per cent and 8 per cent. This variation is attributed to different surface conditions.

Surfaces which have been roughened with coarse alundum cloth and washed in alcohol or benzene give results similar to sand-blasted surfaces, as do freshly machined (rough lathe turned) steel surfaces. We found no treatment of a steel surface, prior to its insertion into the vacuum chamber, which would cause its efficiency of condensation to be higher than that of a sand-blasted surface.

To simulate conditions existing in an ignitron, the third electrode (on the right in figure 1) was used as an anode, and an average current of 15 to 50 amperes was passed through the tube when it was being used as a half-wave rectifier feeding a resistance load from a 220-volt a-c power source. It was found that the yield obtained from the condensing tubes during alternate one-hour periods when a 15-ampere arc was run in the chamber was 20 per cent higher than that observed during the interspersed one-hour periods when no arc was run. This was taken as an indication that the presence of the arc raised the pressure of the mercury vapor in the tube by 20 per cent.

Effect of Negative Voltage Applied to Condensing Surface

The application of a negative potential, with respect to the cathode, to the condensing tube is believed to cause it to be surrounded by a positive-ion sheath during the conducting half cycle. The thickness of the sheath, according to Langmuir's theory of currents to a probe in a plasma, is small in comparison to the diameter of the condensing tube. Positively charged mercury ions then will fall through the sheath and bombard the condensing surface with an energy which is proportional to the potential difference between the arc plasma and the condensing tube. The positive-ion current collected by the condensing tube does not vary as the negative potential of the tube is increased, which is as should be expected if the thickness of the positive-ion sheath remains small, since this current is determined by the random positive-ion current density in the plasma, and all of the positive ions which come to the sheath are drawn to the condensing tube.

The bombardment of the condensing surface by positive ions has a remarkable effect on its efficiency of condensation. The manner in which the efficiency increased as the negative potential was increased is shown in figure 3. These data have been corrected for the increase in mercury-vapor pressure caused by running the arc, as explained earlier. The observed increase in efficiency cannot be explained by the simple collection of positively charged molecules, since the current drawn by the condensing tube and the amount of condensation are of such magnitude that there are of the order of 1,000 mercury atoms collected for each positive charge. Hence, we must conclude that the positive-ion bombardment so alters the condensing surface as to increase its efficiency for

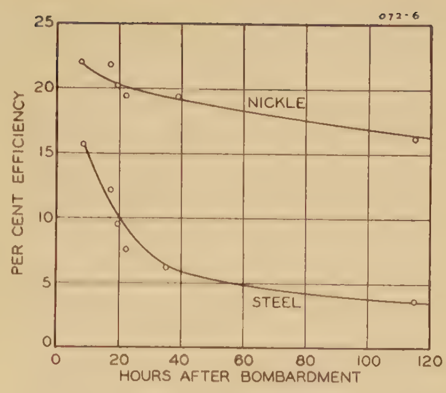

Figure 6. Decay in efficiency after stopping positive-ion bombardment

the condensation of neutral molecules. The efficiency of the condensing surface as a function of time after the arc is turned off is shown in figure 4. The rate at which the efficiency decreases, as well as the value it reaches in a given time, is a function of the length of the preceding bombarding period; if the bombardment has been for a few hours instead of several days, as it was before the data of figure 4 were taken, the efficiency returns to its initial value of less than ten per cent in less than a day.

Condensation on Nickel

The condensation of mercury on a nickel surface was also investigated. One of the steel electrodes shown in figure 1 was replaced by a similar one made of nickel, and in this manner the behavior of the two surfaces was compared under identical conditions. The interesting difference in the rate at which mercury condenses on the two surfaces is shown in figure 5. In this instance, the steel electrode had been bombarded by positive ions before the nickel electrode was placed in the chamber. No arc was run after the insertion of the nickel electrode. The yield from the steel electrode declined as in figure 4, but the yield from the freshly sand-blasted nickel electrode increased during the same interval of time.

When the nickel and steel electrodes are bombarded by positive ions, the maximum yield obtainable from each is similar. After the arc was turned off, the yields from the two electrodes decreased as shown in figure 6.

When two freshly sand-blasted electrodes, one steel and one nickel, were placed in the evacuated chamber and a temperature difference between the mercury pool and the electrodes maintained, the interesting curves of figure 7*a* were obtained. The absolute yields show large fluctuations during the month

period, but the ratio of the yields from the nickel and steel electrodes as shown in figure 7*b* was remarkably steady after the first week. Some of the fluctuations were due to a change in the steady conditions of the experiment during weekends. These changes are noted in the figure.

The much greater condensing efficiency of nickel as compared with steel is remarkable. The initial yields from the two sand-blasted surfaces are always similar, but the rate with which the yield from a nickel surface improves did vary. Thus, as shown in figure 5, the improvement was more rapid than in figure 7*a*. Apparently the rate of improvement depends on the time between sand blasting and the setting up of a temperature difference for condensation.

Effect of Electric Excitation of Condensing Surfaces in Operating Rectifiers

Some preliminary tests were made to determine whether improving the condensing efficiency by positive-ion bombardment of condensing surfaces would give any improvement in performance of operating rectifiers. For these tests

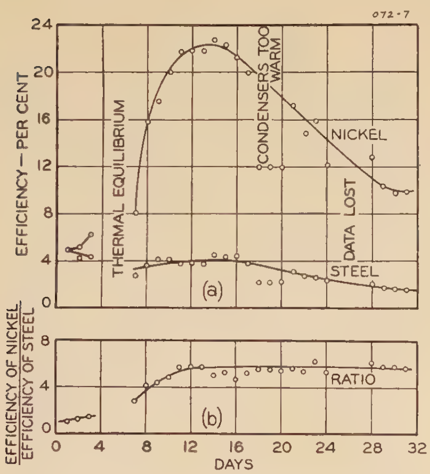

Figure 7. Comparison of nickel and steel condensers over 30 days

we used a pair of ignitrons as a full-wave rectifier, feeding into a resistance load at 8,000 volts direct current. During the greater part of the test, the load current was maintained at 25 amperes, and the condensing surfaces were energized on alternate one- or two-day periods, unenergized on the intervening periods. The number and distribution of observed arc backs are shown in figure 8*a*. The arc backs appear to occur at random during both the energized and unenergized periods. The average number of arc backs per hour was 0.862 and 0.08, a reduction of more than ten by the energized, and the immediate ability to operate satisfactorily when the surfaces were energized were verified by data similar to that in figure 8*b* several times.

However, when the tubes were being operated at 3,000 volts direct current,

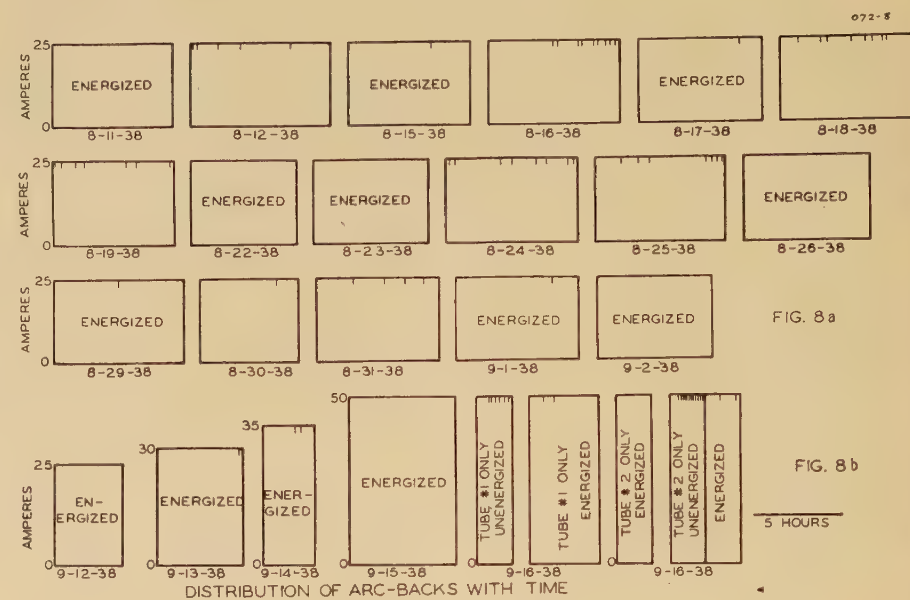

Figure 8. Plot of arc-backs observed with two ignitrons feeding an 8,000-volt 25- to 50-ampere resistance load

Arc-backs indicated in figure 8a are for either tube, those in figure 8b are for the individual tubes

application of potential to the condensing surfaces.

The first part of the test was concluded by the failure of the mechanical vacuum pump. After the ignitrons had again been treated out, a short test was made at higher currents, to 50 amperes. The data of this test are shown in figure 8*b*. An entire day without a failure was obtained while the condensing surfaces were energized on September 15. The next day the surfaces of one tube at a time were de-energized, and the data for the two tubes are shown separately. Both tubes operated satisfactorily for a while, but the one whose condensing surface was de-energized soon began to fail. Tube 2, when de-energized, ultimately became so bad that it would not carry the load for as long as one minute. When the surface was energized, it failed only twice in the following two hours. This complete failure to carry the greater load of 50 amperes when the surfaces were not

and the arc backs occurred infrequently, no definite improvement was obtained by the application of potential to the condensing surfaces. Similar tests on larger ignitrons at 600 volts also failed to show conclusively that arc backs were reduced in number by improved condensation.

Summary and Conclusion

1. Very low condensing efficiencies for mercury usually less than ten per cent were found for water-cooled steel surfaces under conditions simulating those obtaining in practical steel-tank rectifiers.

2. Positive-ion bombardment of condensing surfaces caused a great increase in their condensing efficiency.

3. Nickel surfaces usually showed a condensing efficiency several times as large as for steel surfaces.

4. Positive-ion bombardment of the condensing surfaces of an 8,000-volt d-c 25-ampere single-phase ignitron rectifier greatly improved its operating performance. Similar treatment of a 3,000-volt 200-ampere single-phase ignitron, however, gave no improvement in performance.

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Electric Power for Airplanes

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MEMBER AIEE

Synopsis: Electric-power loads are increasing rapidly on airplanes and auxiliary-engine-driven generators offer dependable power sources independent of main engines. Minimum weight for the required capacity is essential in the design of generators, motors, and control. The a-c 110-volt 400-cycle three-phase system has been developed for large airplanes with heavy motor loads. Alternators rating 12.5 kva at 75 per cent power factor and two-pole motors running at 22,500 rpm full-load speed are available. Control apparatus builds up the alternator, establishes accurate voltage regulation, and provides direct current for excitation and battery charging. The 24-volt system is applied on airplanes using d-c power which have relatively light motor loads. Generators rate 5 kw and are designed for speeds ranging from 3,200 to 6,000 rpm to conform to prime-mover requirements. Motors have been built which run at 7,500 rpm. The control effectively regulates the voltage, handles battery charging, and provides for starting the power plant.

Featherweight Electrical Apparatus

An engineer intently watches the speeding motor shaft—so fast that it is just a blur to the eye. The light of the stroboscope is turned on it and the shaft is seen stationary. The surface of the small 22,500-rpm rotor of the six-horsepower motor travels the distance from New York to Chicago in less than four hours. This is one of the impressive electrical developments for airplanes wherein speed goes up and weight comes down. There is an insistent demand to save "pounds" in aircraft electrical equipment and thus increase "pay-load" capacity. Featherweight generators, motors, and control are now available for such applications.

Airplane Electric-Power Problems

The growth of electric-power loads on airplanes coincides with increases in size, speed, and flying range. Aircraft developments have been extensive during the past few years, resulting in substantial boosts in the uses of electrical energy. Small 6- or 12-volt d-c automotive-type generators, either main-engine driven or located in the air stream, have long served as power sources. These low-voltage systems are inadequate for modern airplanes because of low weight

Figure 1. Aircraft alternator

This is a 400-cycle three-phase machine and is rated 12.5 kw, 120 volts at 75 per cent power factor. It weighs close to 100 pounds

efficiency. It is necessary to apply large generators operating at relatively high voltage to assure economic installations. The result has been the development of the auxiliary-engine-driven power plant, trial of the five-kw main-engine-driven generators, and investigation of steam, hydraulic, and exhaust gas turbines as prime movers.

The auxiliary-engine-driven generator offers a satisfactory means of power supply, continuously available under all operating conditions, independent of the main engine. Units are designed to secure minimum weight for a specific flight time. This requires consideration of the weight of the fuel, oil, engine, generator, and control as well as the efficiency of the plant. Low fuel and oil consumption, which means high engine efficiency, are pertinent in equalizing the weight of fuel and oil with that of the engine. The generator requires the same consideration. A balance must be reached for generator active parts in comparison with fuel and oil weight for a given flight period.

Motors are being extensively used to perform various functions on airplanes. Light weight is essential and in this case, efficiency, the duty cycle, and ventilation affect design. Here again, efficiency has a bearing on the power used and can be evaluated in terms of fuel and oil weight. However, the duty cycle is a factor since high efficiency becomes progressively more important in terms of fuel and oil weight for momentary, intermittent, and continuous operation. Motor weight will go up with decreased ventilation which makes it desirable to limit the use of explosion-proof and enclosed types.

110-Volt A-C System

The 110-volt 400-cycle three-phase a-c system is applicable to large aircraft. Alternators have been built and tested which are rated 12.5 kva at 120 volts and 75 per cent power factor, and weigh practically 100 pounds. The machines operate at 3,430 rpm, a speed which is fixed by the prime mover. Rotors have 14 poles and are mounted on engine-shaft extensions to eliminate bearings. The same shaft extension carries a propeller-type fan which provides additional flywheel effect, cools the engine, and ventilates the alternator. Stators are attached directly to engines.

Alternator efficiency is 92 per cent, a figure selected after an analysis of the weight of the complete power plant plus fuel and oil. Above 92 per cent efficiency,

Figure 2. A 400-cycle three-phase a-c aircraft motor

This machine is rated six horsepower at 110 volts and weighs slightly over 15 pounds. When operating at full load the speed is 22,500 rpm

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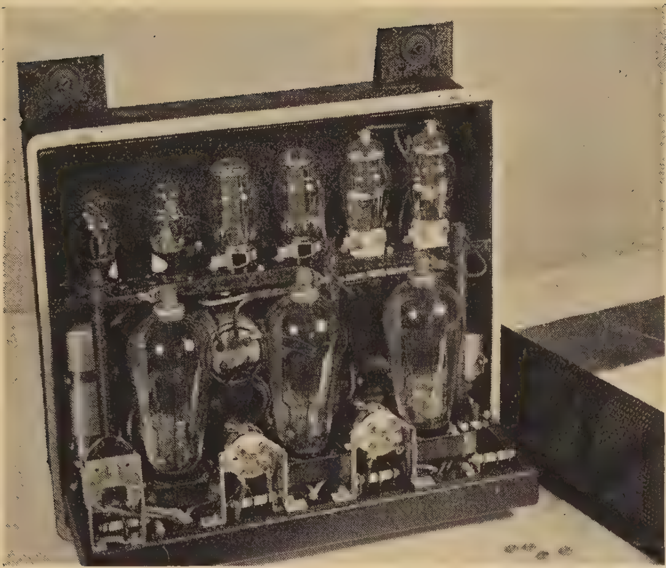


Figure 3. Aircraft electronic voltage regulator used with the 110-volt 400-cycle three-phase a-c system

This device regulates the voltage of each of the three phases and accurately maintains the bus potential

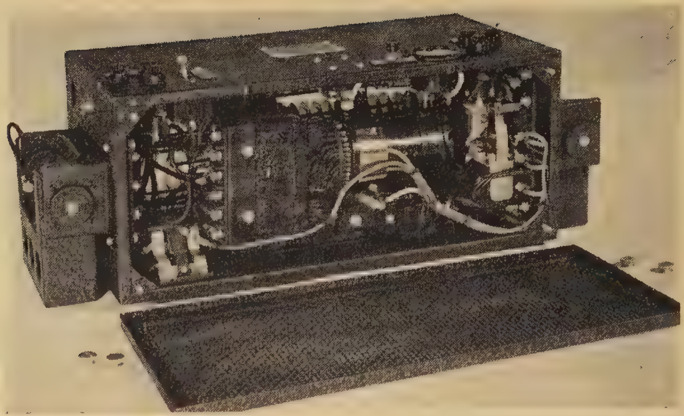


Figure 4. Aircraft battery charger for the 110-volt 400-cycle three-phase a-c system

This dry plate type rectifier furnishes either 14 or 28 volts direct current for battery charging and the operation of d-c auxiliaries

the increase in alternator active parts balances the fuel and oil weight reduction for a 40-hour flight. Overload capacity is determined by sudden load changes, such as may occur with the starting of large induction motors. This is particularly true if the lights and continuous-running motors are operating and momentary starting loads are applied. This condition may reduce voltage too much and consequently alternators are designed for high current overload capacities at low power factors.

Lightweight high-speed induction motors are well suited for 400-cycle three-phase operation. A wide speed range is obtainable by varying the number of poles and machines have been designed to meet many different requirements. Some applications demand high torques for momentary or intermittent use, while others need high efficiency for continuous operation. Two-pole machines have a synchronous speed of 24,000 rpm and normally operate at 22,500 rpm when fully loaded. The larger sizes develop double full-load torque with 3 to $3^1/_2$ times full-load current.

The control regulates the a-c power supply, furnishes 14 or 28 volts direct current for battery charging and d-c auxiliaries, establishes satisfactory parallel operation, and practically eliminates radio or audio interference. The electronic voltage regulator, which has been developed, is faster in response than the mechanical type. Simpler and more positive antihunting methods are obtainable for less weight. It is both a regulator and exciter in one device since d-c field power is provided by rectification from the a-c bus. The regulating tubes are in duplicate to assure reliability. An intermittent-rated Rectox and transformer cause the alternator to build up from its residual magnetism. This function is under the control of a small "Silverstat" regulator which corrects for temperature variations in the circuit resistance. The transfer to electronic regulation is automatic by means of a small thermal timing relay. This method of initial build-up is necessary since sufficient time must elapse for the electronic regulator tubes to reach operating temperature before field current is obtained by rectification.

The engine driving an alternator is started and automatically idled until it reaches operating temperature after which it comes up to normal speed. The alternator switch is then manually placed in the "build-up" position and the voltage rises to normal value under self-excitation and magnetic voltage-regulator control. After some 45 seconds, during which the filaments of the electronic regulator have reached normal operating temperature, the alternator control switch automatically trips to the "run" position. The machine is then under electronic regulation and may be connected to the main bus by closing a circuit breaker. When a second unit is started and is under electronic regulation it may be connected to the bus by closing the circuit breaker. If a reversal of power occurs manual-reset wattmeter contacts function to disconnect the alternator from the bus.

The battery-charging unit consists of a dry-plate rectifier fed from a three-phase transformer through a tap-changing device under control of a mechanical voltage regulator. The rectified voltage is maintained practically constant regardless of load and ambient temperature changes. A central control station contains the alternator circuit breakers, the manually operated build-up switch, and necessary metering equipment.

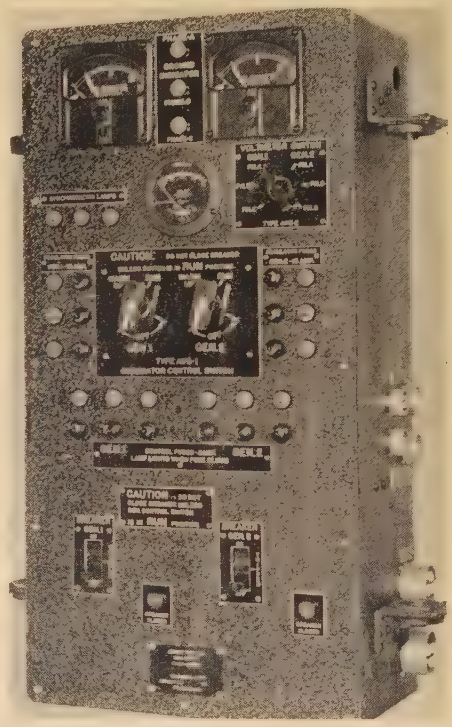


Figure 5. The aircraft control station contains all the necessary instruments and switches for the operation of two 110-volt 400-cycle three-phase a-c power plants

The 110-volt 400-cycle three-phase system is suitable for lightweight radio equipment and is practical for three-phase induction motors. The use of three wires in conduits, together with the

Figure 6. This 4,000-rpm aircraft generator is rated 5 kw, 28.5 volts, 175 amperes. It has a five-minute rating of 7.5 kw. The total weight including the starting switch is just over 50 pounds

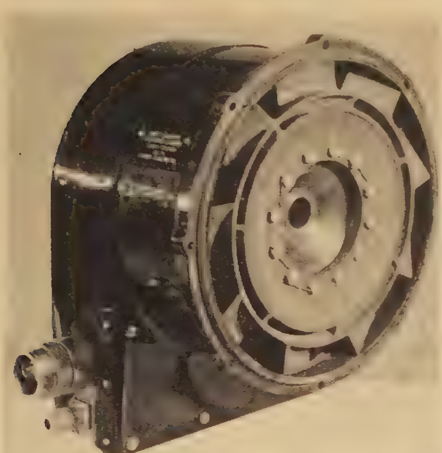
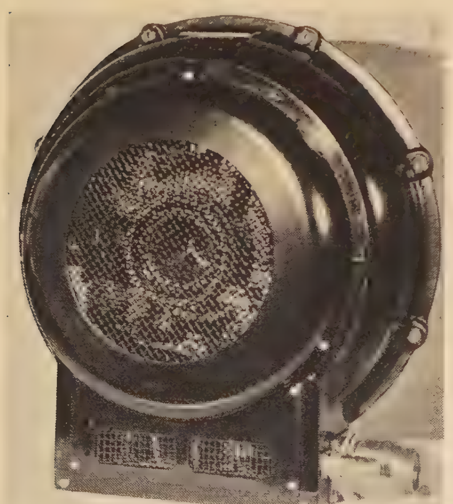


Figure 7. This aircraft generator is in the featherweight class and weighs slightly over 40 pounds including the starting switch. It is rated 5 kw, 28.5 volts, 175 amperes, and will carry 7.5 kw for five minutes. It runs at 6,000 rpm



proper balance of single-phase loads between the three phases, avoids the impedance drops which occur with single phase. Motors will start and produce rated outputs without the use of centrifugal switches, external capacitors, and other control devices. Thus, the system is well adapted for application on large airplanes which make extensive use of electric power and have heavy motor loads.

24-Volt D-C System

The 24-volt system is becoming a standard on airplanes using d-c auxiliary power. Generators have been built which are rated five kw, 28.5 volts, 175 amperes and will carry short-time overloads of 150 per cent normal capacity. Operating speeds are 3,200, 3,430, 4,000, and 6,000 rpm and are determined by the available prime movers. In the case of the 6,000-rpm machine the engine runs at 3,000 rpm. Machines are designed with magnesium-alloy supporting brackets and housings to assure light weight. Fans are magnesium, aluminum, or a heavier metal depending on the added flywheel effect needed for the engine when the armature weight is insufficient. The effectiveness of this weight varies directly as the square of the radius and the fan is the largest-radius rotating member. Special iron alloys are used for the magnetic circuit. Insulation is composed entirely of glass, mica, and asbestos. Generator armatures and fans are mounted on shaft extensions and stators are bolted directly to engines.

It appears that motor speeds will remain at or below 10,000 rpm. The inherent limitations of armature construction and the high starting torques required tend to limit maximum speeds. Motors which have been built run at 7,500 rpm as compared with the much higher speeds practicable with a-c induction types. The materials used and the insulation are essentially the same as for generators.

Figure 8 (left). This aircraft generator runs at 3,200 rpm and weighs just under 70 pounds including the starting switch. It is rated 5 kw, 28.5 volts, 175 amperes, and will carry $6\frac{3}{4}$ kw for 15 minutes

Figure 10(right). This aircraft voltage regulator and reverse-current switch is applicable to the 12-volt d-c system

It weighs under four pounds and maintains accurately regulated bus voltage for 15-volt main-engine-driven aircraft generators

The control regulates the d-c power supply and furnishes charging current for a small battery. It automatically disconnects the battery when the power plant is shut down and functions with little radio or audio interference. The voltage regulator is a small lightweight device utilizing a modification of the industrial Silverstat. Contact maintenance is practically eliminated by distributing the regulating duty over 15 to 20 contacts, each operating safely below the "sparking voltage". Rocking-type bearings, spring restrained, minimize friction and wear.

Change in regulated voltage during the warm-up period has been reduced by using low-temperature-coefficient wire in the regulator coil. Correction for ambient-temperature variation is provided by bimetal compensation of the calibrating-spring tension. The ratio of battery capacity to that of the generator is small, which makes it necessary that the reverse-current device drop out at a small current

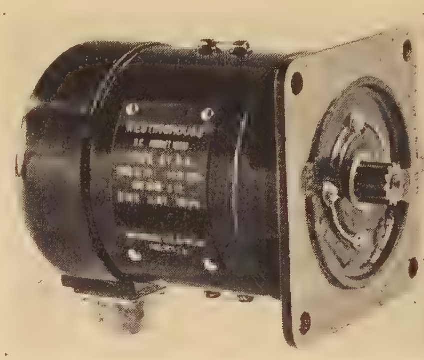
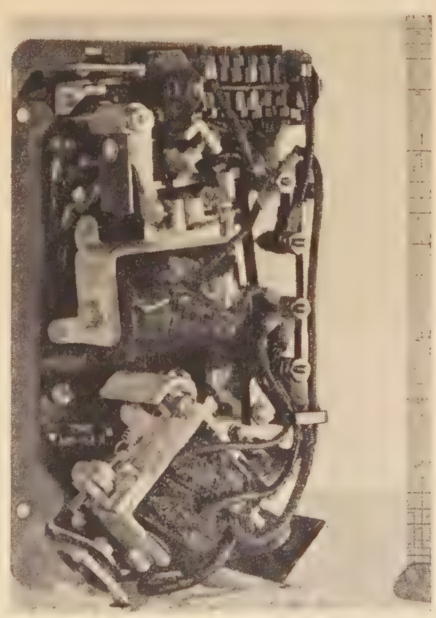


Figure 9. This aircraft motor develops five-eighths horsepower at 25 volts and 7,500 rpm. It weighs close to seven pounds complete



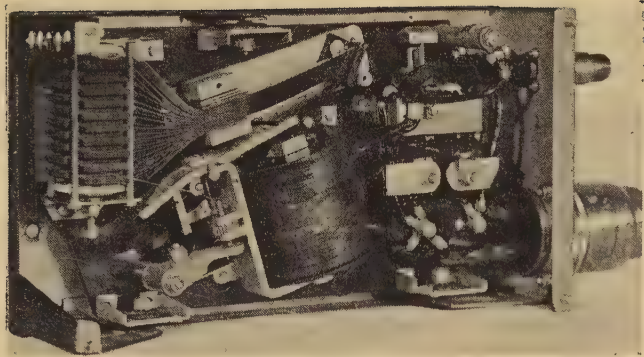


Figure 11. This aircraft voltage regulator and reverse-current relay handles the 24-volt d-c system

It maintains 28.5 volts at the bus. The complete weight including cover is less than nine pounds

value. The relay closes when generator voltage is one volt above battery voltage and opens on less than ten amperes reverse current. It operates the generator contactor which has silver contacts of adequate capacity to handle 175 amperes rated current. By using the generator as a motor to start the engine there is no need for a separate starting motor and its coupling. This combination of functions reduces equipment and cable weights since a separate heavy starting-motor circuit is unnecessary.

The 24-volt d-c system appears to be best for standardizing on one potential for a number of different sized airplanes. It is possible to handle readily battery charging without upsetting present standards. Two 12-volt batteries are applicable, thus facilitating changing from 12 to 24 volts by having 12 volts available during the changeover period. The 24-volt system can be employed advantageously on the lighter types of airplanes which have small motor loads.

New A-C and D-C Apparatus Available

The past 18 months has been a period of intense development of auxiliary engines, generators, motors, and control for airplanes. The two systems now available—110-volt 400-cycle three-phase a-c and 24-volt d-c—meet present requirements and provide for future increases in the use of electric power. The former is well suited for large airplanes with predominating motor loads and the latter is an applicable standard for medium-sized craft with light motor loads.

Discussion

V. H. Grant (United States Navy Department, Washington, D. C.): Mr. Clardy has presented some interesting points on a-c power for aircraft. The Navy, having at least as extensive and complex aircraft electrical systems as exist today, has been undertaking a comprehensive research program on electric power for airplanes. Our results to date do not check entirely with Mr. Clardy's analysis, and a brief summary of our points of difference may be of interest.

First, auxiliary engines for driving generators are extremely expensive, as compared to main-engine drive, in reduced airplane performance and lower useful or pay load. An analysis which we made recently indicates that a 50,000-pound plane suffers less loss in performance by diverting 50 horsepower for auxiliaries from the main engines than in carrying additional auxiliary engines and the extra fuel and oil which they require.

Second, a twin-engine airplane with two auxiliary engines is actually a four-engine plane, insofar as maintenance and overhaul are concerned. The small engines are almost as complex to overhaul as are main engines.

Third, valuable space in the plane must be appropriated, and made soundproof and fireproof, for auxiliary engines.

Fourth, auxiliary engines present an unnecessary additional target, in the case of military planes.

True, main engines are "cleaned up" by the use of auxiliary engines, and a constant drive speed is obtained, permitting the use of a-c generators but these advantages are gained at a considerable penalty. And, whether we want alternating current after we have provided for its generation is questionable, at least for our peculiar requirements. Some of the arguments on this matter may be summarized as follows:

1. Practically all our motors are of the momentary-duty type, requiring high starting torque; they are designed on the basis of torque rather than heating. A d-c series motor is ideal for this service.

2. D-c generators use simple regulators and may be paralleled easily.

3. Battery stand-by may be used for vital services and for peak loads.

4. Much of our load, if alternating current, would be operated from a single-phase source. Load balancing during emergency operation would probably keep the poor flight engineer too busy to do anything else.

5. Voltage diversity would be simplified, but, to date, radio equipment, the only load requiring voltage change, cannot be operated in parallel with fluctuating power loads, owing to the light weight master oscillator circuits being very critical of supply voltage.

6. High-speed motors, although very light in weight, require gear reducers of considerable weight to provide usable speeds. Starting these motors with their low torque, at low temperatures with the gear box grease congealed, may be a problem. Also, the matter of bearing design and lubrication is by no means solved.

7. Conductor weights are smaller with direct current due to fewer wires, and to the absence of the power-factor problem; the power factor of an induction motor when starting is notoriously low.

Mr. Clardy has mentioned high efficiency of equipment. Our studies, so far, indicate that generators, conductors, motors, etc., should have just about as low efficiencies as possible without burning up. The reason is, of course, the weight saving possible by "forcing" the equipment far beyond its maximum efficiency. Weight, in general, appears to be more important in determining airplane performance than power input.

It is the intent of my remarks to promote further discussion and thought on this matter, which is by no means settled. The Navy will benefit as much as anybody from the final solution to the aircraft auxiliary-power problem, and will appreciate any other remarks.

W. J. Clardy: Aircraft auxiliary-engine-driven power plants appear essential for ground or sea-level service in order to avoid main-engine operation for furnishing auxiliary power. Increase in the use of such units will, naturally, lead to improvements to give better weight efficiency. The accessibility, dependability, and small size of the auxiliary engine makes it relatively simple to inspect and maintain. Growth in the use of electric power on airplanes has stepped-up generator sizes. Gear boxes and drive shafts are needed for main-engine drives and the mechanical problems become acute in the case of large units. A main-engine-driven generator, drive shaft, and gear box should be just as good a target as an auxiliary-engine-driven generator—perhaps better since fire may be concentrated on main engines.

The 110-volt 400-cycle three-phase a-c system has been developed to meet the demand for more power—10, 12.5, and 20 kva in single power plants. Alternators are easily paralleled by merely bringing a second machine up to speed and closing the circuit breaker to connect it to the line. Batteries and battery chargers are used with the a-c system but it seems desirable to keep such heavy power sources to a minimum in the interest of weight economy. The proper balancing of single-phase loads can be worked out in advance of any emergency. It is entirely practicable to build light-weight radio equipment for the 110-volt 400-cycle three-phase system and voltage regulation is extremely accurate.

Light-weight high-speed induction motors are well adapted for 400-cycle three-phase operation. High starting torques are obtainable and alternators are designed for high current overloads at lowered power factors to avoid impairment of voltage regulation. Two-pole induction motors run at 24,000 rpm synchronous speed. Lower speeds are secured by increasing the number of poles. In a weight analysis it is necessary to include gearing required for a motor but even on this basis high speed is advantageous. This seems to be borne out by the universal trend to higher speeds. A lubrication system has been evolved for 24,000-rpm motors which appears to be satisfactory under all service temperature conditions.

An airplane with an extensive motor load requires high voltage to avoid exces-

Some Impulse-Voltage Breakdown Tests on Oil-Treated Paper-Insulated Cables

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Synopsis: Data are presented on impulse-voltage breakdown values obtained on oil-treated paper-insulated cables over the insulation thickness range from 0.187 inch to 0.600 inch. The average stress at breakdown approximates 1,600–1,700 volts per mil. High-density papers show some superiority over ordinary-density papers. Cathode-ray oscillograms of the testing wave ($1^1/_2$x40 impulse wave—positive polarity) before and at breakdown are included for a typical test.

INFORMATION on the impulse strength of high-voltage apparatus has accumulated steadily in the last 20 years due particularly to advances in technique of generation and measurement of high-voltage surges. Line insulators, bushings, transformers, and other apparatus have been tested. Cables have received attention during the last decade of this period, and the literature is beginning to record this information.[1,2]

This paper presents data on the impulse breakdown voltage of oil-treated paper-insulated cables over the range of insulation thickness from 0.187 inch (0.472 centimeter) to 0.600 inch (1.520 centimeters). The impulse breakdown voltage at the latter thickness was of the order of 1,000,000 volts. Cable breakdown tests are necessarily destructive of the sample and involve many samples and a costly preparation procedure. Data thus accumulate more slowly than in cases involving air flashover. These data have been accumulated over the period 1931 to 1938. The testing technique has differed somewhat during this period; early tests employed a 1x10 wave (that is, one microsecond to crest voltage, ten microseconds to decrease to one-half crest voltage); later tests employed a $1^1/_2$x40 wave. In all cases a positive impulse was applied to the cable conductor, the lead sheath being connected to ground.

The tests on the thinner (0.187 inch) insulation were made on samples having ten feet of lead. The ends were built up with a varnish-cloth reinforcement over which was placed a spun-copper stress-distributing bell. This latter was connected to the sheath by a closely wrapped spiral copper braid on the lower slope of the varnished-cloth reinforcement. The whole cable was then immersed in an oil-filled tank. All other tests were made on 16-foot (lead length) samples using standard porcelain oil-filled terminals of usual design. All cable failures secured were in the leaded portion of the cable.

Impulse Generator

The impulse generator used for these tests has a 2,000-kv open-circuit rating and is of the parallel-charging, series-discharging type. The d-c charging voltage is 200 kv for each of the ten parallel capacitor banks. The generator has a series capacitance of 0.0067 microfarad and a circuit inductance of 75 microhenries.

The circuit arrangement used is shown in figure 1. The wave-front time is determined by the resistance-capacitance combination R_1C_2 and the wave tail by the resistance R_2 and the combined capacitances C_1 and C_2. The determination of these values is done experimentally and without delay on the oscillograph electric-transient analyzer.[3,5] All oscillograph records were taken with the type HC-15[4,5] hot-cathode high-vacuum high-voltage cathode-ray oscillograph.

Table I. Specimen Sphere Gap–Cathode-Ray Oscillograph Calibration Check

	Surge-Generator	Sphere Gap (100 Cm)			Cathode-Ray Oscillograph				
No.	Excitation, Volts	Setting (Cm)	Voltage (Kv)	Corrected Kv	Millimeters	Volts	Ratio	Kv	Deviation (Per Cent)
10	40	3.59	100	105	22.2	913	113	103	−1.3
11	40	3.59	100	105	22.2	913	113	103	−1.3
12	40	3.59	100	105	15.5	637	162	103	−1.6
13	40	3.59	100	105	15.5	637	162	103	−1.6
14	78	7.62	200	210	31.0	1,274	162	207	−1.5
15	78	7.62	200	210	30.8	1,266	162	206	−2.1
16	78	7.62	200	210	21.8	897	228	204	−2.8
17	78	7.62	200	210	22.1	909	228	207	−1.5
18	119	12.53	300	315	34.5	1,418	228	323	+2.4
19	119	12.53	300	315	34.2	1,406	228	320	+1.6
20	119	12.53	300	315	24.5	1,007	328	330	+4.6
21	119	12.53	300	315	23.2	995	328	326	+3.3

Pressure, 77.37 centimeters mercury; temperature, 14 degrees centigrade; relative air density, 1.056; gap correction, 1.052.

Demonstration of Measurement Accuracy

Standard procedure used in these tests for calibration of the surge generator is given in the recently revised AIEE Standard No. 4, "Measurement of Test Voltage in Dielectric Tests". This calibration recommends an intercomparison between sphere gap and cathode-ray oscillograph for demonstration of measurement accuracy. These intercomparisons were made at frequent times during this cable-testing program. Record of one such comparison is reproduced in table I. The deviation between sphere gap and oscillograph

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C. M. Foust and J. A. Scott are in the general engineering laboratory, General Electric Company, Schenectady, N. Y.

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1. For all numbered references, see list at end of paper.

sive weight in the distribution lines. This seems to eliminate the 24-volt d-c system when a large number of motors is used. At 110 volts, the 400-cycle three-phase a-c system offers some attractive weight-economy possibilities because of high-speed induction motors. In considering auxiliary-power-plant efficiency on airplanes it is obvious that "weight efficiency" is the determining factor. In the analysis of an auxiliary power system there is no question about its importance. "Weight efficiency" requires consideration of the fuel, oil, engines, generators, control, distribution system, motors, lights, radio, and any other loads. The efficiency of a specific part of the system must be selected to attain the lowest total weight.

Table II.

Specimen Breakdown Test on High-Voltage Cable

Thickness 315 Mils, $1^1/_2$x40 Wave

Number	Surge Generator (Volts)	Cathode-Ray Oscillograph: Deflection Mm	Deflection Volts	Divider Ratio	Kv	Time to Breakdown (μ Sec)
1	56.0	10.4	427	773	329	
2	60.5	11.4	468	773	362	
3	64.5	12.3	506	773	391	
4	68.0	13.0	537	773	415	
5	72.0	14.0	576	773	445	
6	75.0	14.7	605	773	467	
7	78.0	15.5	635	773	490	2.6

Time-Scale Calibration

Number	Frequency (Cycles Per Sec)	Time Scale (μ Sec)
8	500.000	5.9 average

Deflection Calibration

Number	Applied Voltage	Deflection Mm	Deflection Volts Per Mm
9	250	6.3	39.6
	500	12.0	42.5
	750	18.3	41.1
			41.1 average

Table III. Impulse Breakdown Values for 33 Cables Having Oil-Treated Paper Insulation Ranging From 0.187 Inch to 0.600 Inch Thick, Tested at 25 to 30 Degrees Centigrade

Cable Number	Conductor Size (Stranded)	Thickness of Insulation (Inches)	Paper Density	Oil Viscosity at 100 Deg F (Saybolt Sec)	Impulse Breakdown (Kv Crest)‡
1	00 Brown and Sharpe*	0.187	0.8	2,500	350
2	00 Brown and Sharpe*	0.187	0.8	2,500	350
3	00 Brown and Sharpe*	0.187	0.8	2,500	350
4	00 Brown and Sharpe*	0.187	0.8	2,500	350
5	00 Brown and Sharpe*	0.187	0.8	2,500	350
6	00 Brown and Sharpe*	0.187	0.8	2,500	375
7	00 Brown and Sharpe*	0.187	0.8	2,500	400
8	2,100,000 circular mils**	0.315	1.0–1.1	100	610
9	2,100,000 circular mils**	0.315	1.0–1.1	100	512
10	2,100,000 circular mils**	0.315	0.8	100	448
11	2,100,000 circular mils**	0.315	0.8	100	453
12	2,100,000 circular mils**	0.315	0.8	100	461
13	2,100,000 circular mils**	0.315	40 per cent 1.0–1.1, 60 per cent 0.8†	100	500
14	2,100,000 circular mils**	0.315	40 per cent 1.0–1.1, 60 per cent 0.8†	100	490
15	2,100,000 circular mils**	0.315	Medium density	100	555
16	2,100,000 circular mils**	0.315	Medium density	100	559
17	2,100,000 circular mils**	0.315	Medium density	100	559
18	2,100,000 circular mils**	0.500	1.0–1.1	100	730
19	2,100,000 circular mils**	0.500	1.0–1.1	100	765
20	2,100,000 circular mils**	0.500	0.8	100	630
21	2,100,000 circular mils**	0.500	0.8	100	648
22	2,100,000 circular mils**	0.500	40 per cent 1.0–1.1, 60 per cent 0.8†	100	902
23	2,100,000 circular mils**	0.500	40 per cent 1.0–1.1, 60 per cent 0.8†	100	928
24	2,100,000 circular mils**	0.500	40 per cent 1.0–1.1, 60 per cent 0.8†	100	940
25	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	1,067
26	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	1,104
27	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	1,115
28	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	856
29	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	916
30	500,000 circular mils§	0.600	40 per cent medium, 60 per cent 0.8†	100	836
31	500,000 circular mils§	0.600	Medium density	100	896
32	500,000 circular mils§	0.600	Medium density	100	940
33	500,000 circular mils§	0.600	Medium density	100	1,014

* Stranded; 0.420 inch outside diameter. Solid-type cable.
** Hollow core; 1.890 inch outside diameter. Oil-filled cable.
§ Hollow core; 1.03 inch outside diameter. Oil-filled cable.
† Graded insulation with higher-density paper next to the conductor.
‡ Wave shape of first seven tests was 1x10, of all others $1^1/_2$x40 as defined by (microseconds to crest) – (microseconds to half value).

is below five per cent for this record and for all comparisons made during these tests, satisfactory accuracy for such measurements.

Testing Procedure and Calibrations

The routine followed in applying the impulses was as follows. The generator having been adjusted to give the desired

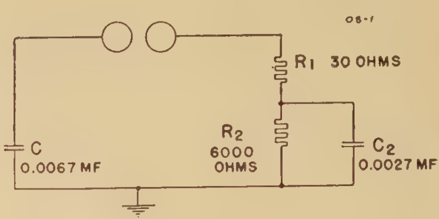

Figure 1. Impulse-generator circuit schematic diagram

Constants shown are for the cables of group C of figure 3

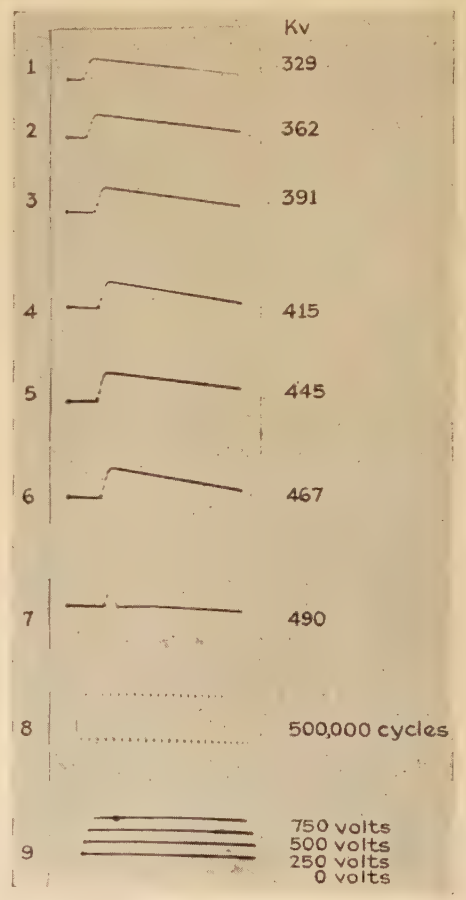

Figure 2. Specimen oscillograph record of impulse-breakdown test on cable sample with calibrating records

1–6—Successively applied impulse-voltage waves of increasing crest value

7—Impulse wave producing cable failure

8—Oscillator wave for time-axis calibration

9—Direct-voltage records for deflection calibration

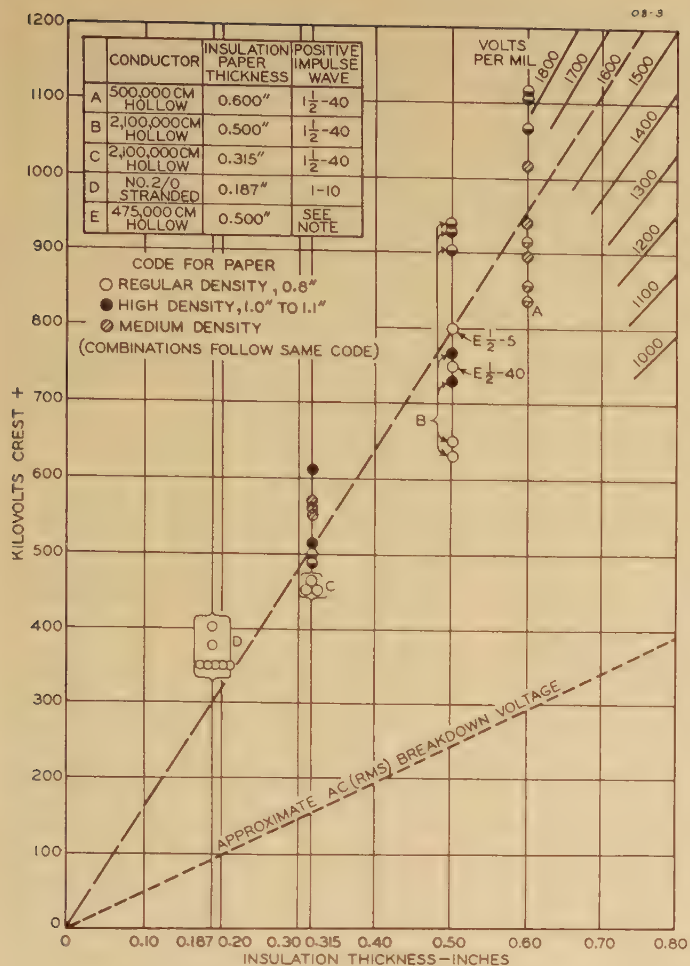

Figure 3. Summary of impulse tests on cable insulation

wave shape and its excitation calibrated in terms of crest kilovolts, an impulse was applied to the cable of a magnitude well below (approximately 50 per cent) expected breakdown. Successive single waves were then applied, each exceeding the previous wave by an approximately constant increment until a cable-insulation breakdown was obtained. Failure was indicated in the tests made in 1931 by the action of a surge-crest ammeter[6] inserted in the ground lead from the cable sheath; in all tests made since that time a cathode-ray oscillograph[6] was employed using a resistance voltage divider, and an oscillogram was obtained of each wave up to and including the one causing failure. The magnitude of the crest voltage was obtained from the cathode-ray oscillograph deflection and voltage-divider ratio as indicated in table I. Practically all failures occurred on or near the crest of the wave.

Specimen Record

A specimen oscillograph record is reproduced in figure 2 wherein are recorded the six full ($1^1/_2$x40) waves at increasing voltage amplitudes followed by the wave at 490 kilovolts crest which caused cable failure. The eighth record is that of a 500,000-cycle timing wave and the ninth a deflection calibration. The data pertaining to all these are given in table II. The recorded waves were analyzed to be 1.55 microseconds to crest and 39.3 microseconds to half value on the wave tail.

Results

Figure 3 shows the results obtained in these tests. Plotted here is kilovolts crest against insulation thickness. Table III records the numerical values. No attempt has been made to draw a curve through the points. In fact, the dispersion is such that a straight line fits the data as well as does a curve. A polar-co-ordinate system has been superimposed from which the average stresses (volts per mil) may be read. An average figure of 1,600 volts per mil may be carried in mind as representative.

It is not attempted to take account of the stress variation between conductor and sheath, although conductors from number 2 Brown and Sharpe to 2,100,000-circular-mil hollow with outside diameters of 0.420 inch and 1.890 inch respectively were used. The tests included several grades or densities of papers, and in general the denser papers gave higher breakdown values. In the presence of the natural variation or dispersion of the results, including the fact that many samples included graded insulations, an accurate statement cannot be made comparing the different densities. We may perhaps infer that the dense papers yield results 10–15 per cent better than the lower-density papers.

The results reported in this paper are in excellent agreement with those reported by Held and Leichsenring,[2] who tested over nearly the same range of insulation thickness.

All the tests here reported were made with positive polarity and with waves of 1 to $1^1/_2$ microseconds wave front. However, as far as analysis of breakdown values reported herein are concerned, the wave-shape change is not important. The wave fronts were practically the same, and failures occurred most frequently on or near the wave crest. A 1x10 wave was used on the earlier tests as a compromise between the 1x5 and $1^1/_2$x40 waves then most common. Later, as the 1x5 wave diminished in use, all tests were made with the $1^1/_2$x40 wave. These waves are those in most common use in this country for impulse testing.

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Discussion

Herman Halperin: See discussion, page 399.

P. L. Bellaschi and W. L. Teague: See discussion, page 400.

L. G. Smith: See discussion, page 401.

J. H. Hagenguth (General Electric Company, Pittsfield, Mass.): Several years ago tests were made in the high-voltage engineer-

ing laboratory in Pittsfield to determine the volt-time characteristic of a cable. Although in general high-voltage cables probably are not subjected to steep-fronted lightning waves, it might be of interest to publish the result.

The cable sections tested were prepared similarly to the samples described in the paper with the exception that the leaded portion was only ten inches long as compared to ten feet in the paper. The total length of a sample was $4^1/_2$ feet. The whole section was immersed in oil. All failures occurred in the leaded section.

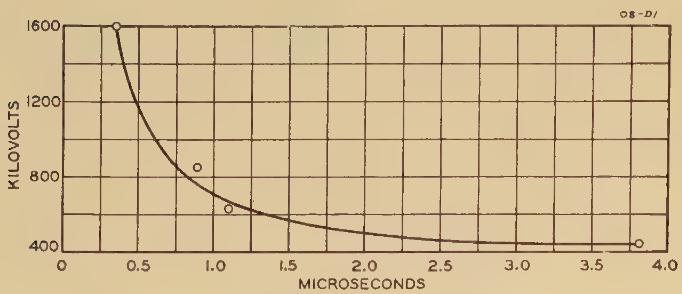

Figure 1. Volt-time curve of breakdown on lead-sheathed cable

Negative polarity, 1.5x40 wave

The cable had a conductor of 500,000 circular mils, 0.281-inch paper insulation, oil treated, and a total outside diameter of 1.6 inches. Tests were made with negative polarity.

For determining the minimum breakdown strength, tests were started at a voltage of approximately 60 per cent of the expected failure voltage. Voltage was raised in about 25-kv steps until failure occurred at 440 kv. Two impulses were applied at each step.

The breakdown voltage thus obtained is probably somewhat too high for design purposes, because it does not take into account the effect of successive strokes on the breakdown. In transformer insulation the damaging corona level is reduced to 80 per cent of the single-shot corona level, when 15 or more impulses are applied. In a cable with its more uniform field and uniform insulation, the multishot breakdown probably is not quite as much lower as in transformer insulation but nevertheless their effect must be taken into account to arrive at the proper safety factors.

The other three sections were tested by applying various amounts of overvoltage to the cable and recording the resulting failure by means of a cathode-ray oscillograph. For the purposes of the investigation described, the few breakdown points obtained showed results which gave a sufficiently consistent curve as shown in figure 1 of this discussion. However, a greater number of points and different thicknesses of insulation would have to be investigated for design data.

Of interest is a comparison of the overvoltage characteristics of various electrode shapes in comparison with the cable. This is shown on figure 2 of this discussion for a 20-inch rod gap, a 10-centimeter sphere gap at 20 centimeters spacing and the cable.

It is interesting to note that the cable in spite of the relatively uniform field has a much steeper characteristic than the sphere and even approaches the characteristic spark-over curve of the 20-inch gap at 0.5 microsecond. The reason for this behavior may be imperfections in the lead sheath producing point effects and corona on the positive sheath.

R. W. Atkinson (General Cable Corporation, Perth Amboy, N. J.): In regard to surge strength of paper in cable we have been for some time depending upon a number of tests made in 1931. It is gratifying to observe the close agreement between these and the more complete series reported by Foust and Scott. Besides our data in direct line with Scott's we are reporting here some tests tending to answer some of the questions which have been asked.

Our tests were made on cables with an insulation thickness of 190 mils, which is identical with the thickness on which a number of tests were made by Scott. The average value of 12 tests directly comparable with his was 348 kv, which is almost exactly the same as the value shown for a group of his tests on corresponding cable.

The tests included in the above group were all made with surges of positive polarity. A few tests were with surges of negative polarity. These required slightly higher voltage to produce breakdown than required for breakdown of similar cable tested with positive polarity.

Half of the samples were made with paper of high density and half of lower density. The average strength of those with high-density paper was 18 per cent greater than for those of low density. It is noted that this is somewhat greater than found by Scott but reasonably comparable with his figures.

Two longer lengths were subjected to 83 and 115 repeated surges respectively. In the first surges, the applied surge voltage was about 60 per cent of the expected surge breakdown. Ten shots were applied after which the applied voltage was increased by about 6 per cent of the expected breakdown. A third set of ten shots at 6 per cent higher voltage was then applied, after which successive sets of ten shots each were applied with voltage increments of 3 per cent until failure occurred.

While the voltage of the ten successive shots at one setting was substantially the same, this repetition would not be exact. Thus the fact of failure at other than the first shot at one voltage may be due either to the cumulative effect of successive shots at substantially the final breakdown value or may be due to a slightly greater voltage at the surge producing failure than on the preceding surges at the same nominal voltage.

On one of the lengths, 35 of the shots were at a value within 10 per cent of the average surge breakdown of similar cable and the breakdown occurred after the cable had stood two surges at the breakdown setting. On the other, 33 of the shots were above the average surge breakdown of similar cable and the surge breakdown occurred after four surges at the same setting without failure.

Another portion of the same cable was tested similarly at 60 cycles but without the application of the surge voltage. The breakdown voltage on the "surged" and "unsurged" samples fell within the same range and thus there was no evidence from these tests that the 100 surges had produced any reduction in strength of the insulation.

The tests of this last named series appear reassuring with respect to the possibility of partial puncture by lightning being followed by subsequent failure at power frequency. Actually the result could have been fully anticipated from analysis of the relation between strength and length of time required for failure. These tests do not throw light on the possibility of a puncture from lightning not followed at once by power failure, but producing damage that leads to subsequent failure.

The appearance on dissection of surge failure not followed by power failure in paper cables, is of some interest. These were found to be tiny radial holes, the paper being "burred," as by being punctured by a minute fast projectile from the conductor, there being no apparent burning.

With the increasing knowledge of the magnitude of surge voltages which can take place on a system, and of the amount of resistance of cables to such disturbances, the danger from this cause of failure has been diminished very greatly.

L. I. Komives (nonmember; The Detroit Edison Company, Detroit, Mich.): First of all the authors of this paper are to be congratulated for the valuable data which they collected in a field largely unexplored.

1. I am rather puzzled with the results presented in this paper because the voltage

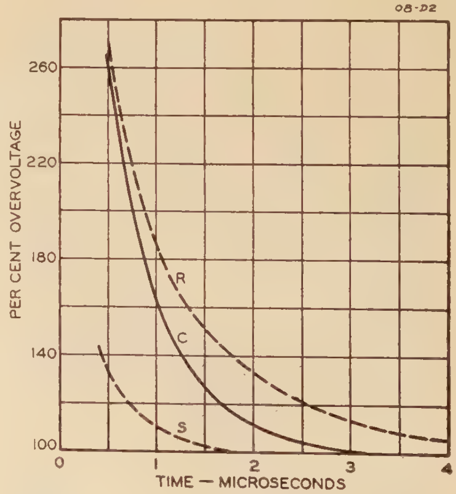

Figure 2. Negative-voltage characteristics

C—Cable, 0.281-inch oil-treated paper (440 kv critical)

R—Rod gap (410 kv critical)

S—Sphere gap (450 kv critical)

100 per cent equals critical breakdown voltage

gradient seems to have had no effect whatsoever on the impulse strength of the cables tested by the authors. In our rather incomplete experiments we found that the voltage gradient has a very strong influence on the impulse strength.

2. We have also found that uniformity of the taping has a very decided influence on the impulse strength. No mention whatsoever was made in the paper in this respect.

3. I feel that the results shown on small-size copper conductors (samples 1 to 7—table III) are due to a highly viscous oil used in these cables in contrast with the much lower viscosity oils of the rest of the samples. I would like to know whether the authors concur with this explanation.

4. We feel that it is perhaps of more importance to cable users to know just what the impulse strength of a piece of cable is when tested with the maximum potential available. Although the general opinion is that potentials lower than those causing breakdown of the insulation have practically no effect on the insulation because of the short time involved, we have reasons to believe that every application weakens the insulation and therefore, testing cables with consecutively high potentials does not indicate the true impulse strength of the insulation.

5. I would like to know what the "medium density" paper mentioned in table III of the paper is.

Wm. A. Del Mar (Phelps Dodge Copper Products Corporation, Yonkers, N. Y.): The following questions occurred to me in reading the paper:

1. Would any materially different values of volts per mil have been obtained if actual rather than nominal insulation thicknesses had been used?

2. Were any of the cables shielded with copper shielding tapes? Would the use of such tapes, by holding the paper tapes firmly together, increase the impulse strength?

3. With unexplained variation of impulse strength from 1,300 to 1,900 volts per mil on one wall thickness, is it safe to base insulation walls on impulse strengths higher than 1,300 volts per mil?

4. Figure 1 shows a resistor R_1. Is there any reason for preferring this to a reactor?

C. M. Foust and **J. A. Scott:** In J. H. Hagenguth's discussion he has added three front-of-wave short-time breakdown values and a minimum breakdown value on 0.281-inch paper to our test data. The minimum breakdown value is a good check on our values for this thickness, being almost exactly on our average curve. The three short-time values permit an approximation of the volt-time curve from actual test data on cable samples down to 0.4 microsecond. The comparison of rod gap, cable, and sphere gap volt-time curves wherein the cable curve conforms more nearly to the 20-inch rod-gap curve than to the spheres suggests a long breakdown path, possibly in many parts parallel to and between paper layers.

The authors appreciate the discussion contributed by Messrs. Bellaschi and Teague, pertaining to volt-time breakdown relations for short time periods. Other than that the point of breakdown on the wave shape was recorded by cathode-ray oscillograph, no effort was made in our work to gather data on volt-time relations. As pointed out in the paper, all failures occurred at the crest or a short time after, indicating very little increase in voltage down to 1.5 microseconds for wave-crest failures. This, the authors presume, is the basis for the statement by Messrs. Bellaschi and Teague that the volt-time characteristic is essentially constant down to one or two microseconds. However, Mr. Hagenguth's data which was taken on the wave front indicates a 20-per cent increase in voltage at 1.5 microseconds. This is likely due to the fact of the wave-front failures being higher than wave-crest values at the same time point.

In commenting on L. G. Smith's discussion, he is correct in presuming that the values are for new cable. We agree that similar data on cable having been in service for some time are desirable. It seems logical to expect that there should be no change in impulse strength with age for oil-filled cable, while solid-type cable might show a decrease due to void formation. The point of variation of breakdown strength with conductor size has been twice referred to in the discussion with the inference that our tests showed no such variation. We did not wish to convey this impression. To determine such a relation accurately would require a large number of tests with different sizes of conductors and a range of insulation thicknesses for each. Such a test program on high-voltage cable samples is quite formidable. We wish to say that because of the dispersion of our test points analysis of the data did not provide us with a sufficiently definite relation between conductor size and breakdown to warrant comment.

Mr. Atkinson has referred to a considerable group of data taken by his company. He had very kindly made these results available to us early in our investigation. To show the good agreement between these results as well as those reported by Held and Leichsenring (reference 2 of the paper), figure 3 of this discussion consolidates these together with some other data identified in the figure. It is here seen that all data from some six sources are in excellent agreement. An excellent idea of the spread of the values is given. This spread is very reasonable for such breakdown values.

Mr. Atkinson also refers to the lack of damage done by impulses of value somewhat below the breakdown value. This freedom from so-called "impulse fatigue" is verified in our own experience. For example, in our tests on the samples having 0.187-inch paper, two additional samples were subjected, one to 100 impulses at 325 kv, the other to 500 impulses at 300 kv; following this single impulses at 25-kv increments were applied. Both cables failed at 375 kv which compares with the highest results obtained on samples 1 to 7 reported in the paper. However, an open mind should be kept on this subject, as indeed on all aspects of this relatively young subject, for we have seen unpublished data from abroad where on relatively thin samples several thousand successive shots did produce a decrease in the breakdown value.

In reply to Mr. Komives in the order of his questions:

1. We would agree that voltage gradient is probably the controlling factor in the breakdown

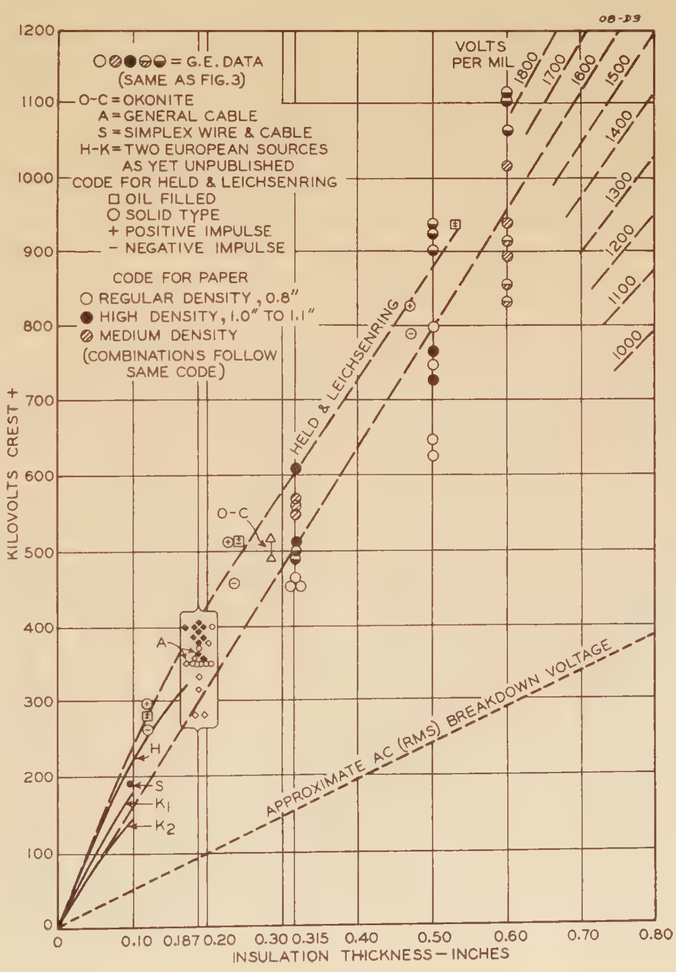

Figure 3. Summary of impulse tests on cable insulation

Impulse Strength of Cable Insulation

E. W. DAVIS
FELLOW AIEE

W. N. EDDY
FELLOW AIEE

INSULATED CABLES often are exposed to lightning and often have been damaged by lightning, especially rubber- or cambric-insulated cables of medium or lower voltage. It is also true that some service trouble has been improperly attributed to lightning. Knowledge of the impulse strength of cable insulation is necessary to analyze such cases correctly and to minimize lightning trouble by proper cable design. In spite of the practical need for such information there seems to be a conspicuous lack of it in the literature.

From time to time for several years we have been making impulse tests on cable insulation, either as we needed the data or as we got the opportunity. As a result we have accumulated a general assortment of data without conducting a complete or continuous investigation. We have found these data worth while and hope eventually to make the data complete enough to merit a more detailed analysis than seems justifiable at present. In the meantime we are reporting the results to date with the hope that the ensuing discussion will uncover results of other tests that have been made but not reported.

Paper 40-34, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 29, 1939; made available for preprinting December 21, 1939; released for final publication February 29, 1939.

E. W. Davis is chief electrical engineer and W. N. Eddy is experimental engineer, Simplex Wire and Cable Company, Cambridge, Mass.

The data in the paper represent the efforts of several people at irregular intervals over the last four years. In particular the authors wish to acknowledge the valuable advice of C. M. Foust in building generator 2 and the conscientious work of S. N. Alexander, W. D. Fenn, and Oscar Hess in calculating and testing.

Impulse Generators

Each testing impulse consists of a nonoscillatory increase and decrease of voltage at a definite rate. Two different impulses have been used for these tests, a 1x10 wave and a 1.5x40 wave. The first figure in each designation is the time in microseconds from the beginning of the impulse to the crest of the impulse. The second figure is the time in microseconds from the beginning to the point on the impulse tail at which the voltage has fallen to one-half the crest or maximum value.

The impulses are generated by discharging a capacitance through a resistance. The resulting voltage drop across the resistance is the impulse. The shape of the impulse is controlled by the values of the constants in the discharge circuit; the impulse front by inductance in series or capacitance in parallel with the resistance and the impulse tail by the resistance itself. The assembly necessary to produce these impulses constitutes the impulse generator.

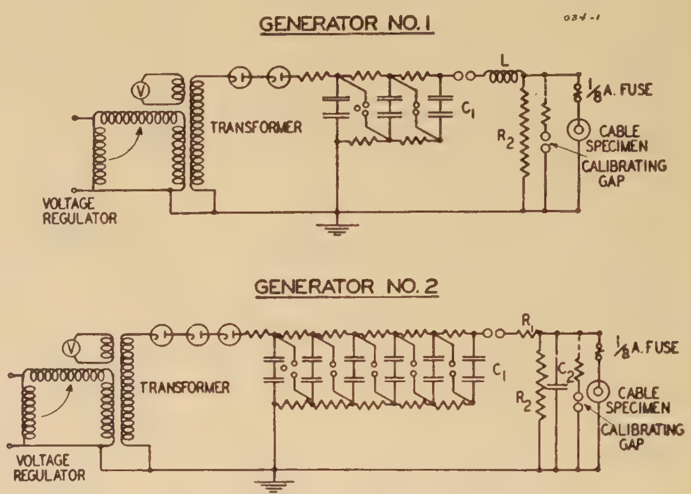

Figure 1. Connections

Figure 1 shows the connections of the two generators that were used for the tests. In both, the necessary high discharge voltage is attained by the familiar Marx circuit which has been fully described in the literature. The differences between the two generators are evident from the connections in figure 1 and the ratings and circuit constants in table I.

Generator 1 was made several years ago, using available glass plates for the main capacitance. The constants in the discharge circuit were adjusted for a 1x10-microsecond wave because this was the intermediate of the three waves then in common use for testing lightning arresters.

Generator 2 was built more recently, in order to enlarge the range of sample length and size that could be tested. The discharge circuit was adjusted to a 1.5x40-microsecond wave because this

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strength. It is, however, only one of a number of variables and we chose the more practical minded way of plotting breakdown against insulation thickness. Conductor sizes are given so that approximate maximum gradients may be calculated if desired.

2. We felt that the uniformity of taping was excellent and found no indication from the examination of the failures to indicate taping to be at fault.

3. We see nothing in our results to lead us to attribute different performance to the two different viscosities of oil used. As a first approximation we would assume them to be identical. Samples 1 to 7 of table III have thinner insulation than the remainder and consequently benefit somewhat by any curvature that may exist in the breakdown voltage-thickness curve.

4. The alternative method of testing referred to by Mr. Komives is highly interesting. We proceeded the way we did because we were on untried ground and we preferred to feel our way along as it were. Our results we feel are more indicative of the lowest breakdowns that might be obtained and consequently more useful in estimating safely sustained voltage values. However, the procedure suggested has its merits and will, we hope, be used. We have already referred to "impulse fatigue" in connection with Mr. Atkinson's discussion.

5. The medium-density paper was a special paper having a density of 0.85 or lower.

Mr. Halperin emphasizes nicely a number of points and gives some valuable suggestions for further work.

Answering Mr. Del Mar in the order of his questions:

1. The difference between actual insulation thickness and nominal thickness was small compared with the variation in breakdown-voltage results.

2. No shielding tapes were used. Since all tests were made on single-conductor cables, which were newly manufactured and whose sheaths had not been expanded by heating and cooling cycles, our results should be the same as if shielding tapes were used.

3. Mr. Del Mar's third question covers a lot of ground. To answer it briefly our consolidated data between 0.315-inch thickness and 0.600-inch thickness regardless of the particular construction of the cables (paper, etc.), indicates the probability that five per cent of such a group of cables would fail at 1,300 volts per mil or less. (Average breakdown, 26 tests = 1,615 volts per mil; $\sigma = 191$ volts per mil or 11.8 per cent of average.) Such variation is typical of breakdown data.

4. Other circuits, of course, than that shown in figure 1 may be used. We preferred a resistor, R_1, to a reactor because of the lesser liability to oscillations which frequently occur when lumped reactors and capacitors are used.

shape had become generally accepted as the standard test wave. The ballast capacitance in parallel with the sample has two functions; to help control the wave shape and to decrease the effect of changing sample capacitance on the wave shape.

Our principal purpose in making these tests was to compare different sizes and types of cable on an impulse reasonably representative of lightning, without attempting to get co-ordination with other impulse data in the literature. Therefore, we have been more interested in keeping our wave shape constant or fixed than in making sure it was exactly 1x10 or 1.5x40. For this reason we have not yet considered it necessary to acquire a cathode-ray oscillograph and our wave shapes therefore have not been confirmed by oscillograph. The test results in table II indicate that the value of our results is not seriously reduced by this omission.

Each test is made by increasing the charging voltage in seven-kv steps usually beginning at 50 per cent of the estimated breakdown voltage. Each voltage is held constant while two successive impulses are applied to the sample by lowering a third sphere into the first-stage gap. Failure of the sample is indicated by explosion of the one-eighth-ampere fuse wire in series with the sample. The test voltage is indicated by a voltmeter coil in the charging transformer calibrated in terms of a sphere gap in parallel with the test sample. Both ends of the sample are connected together. Various arrangements of the sample were tried without finding any effect on the impulse strength.

Table I. Ratings of Impulse Generators

	Generator 1	Generator 2
Maximum discharge voltage at terminals of C_1 (kv)	300	600
Maximum voltage on specimen (kv)	260	550
Main capacitance C_1		
(μf per 50 kv)	0.04	0.5
(μf at full voltage)	0.0067	0.042
Ballast capacitance C_2 (μf)	None	0.0048
Discharge resistance R_1 (ohms)	None	115
R_2 (ohms)	2,300	1,100
Calculated wave shape	1x10	1.5x40

Figure 2 shows the general arrangement of generator 2. At the left is the portable control table connected to the generator through two multiconductor portable cables. The voltage regulator controls the input to the transformer in the corner which through the tube rectifiers charges the capacitors on the wooden rack. The stage resistors consist of water in the garden hose visible along the upper edge of the rack. The third or trigger sphere is visible just above the first stage gap. A sample of plain rubber wire is shown ready for test in water. The series fuse wire is on the framework above the water drum. The motor on the floor is circulating a sodium carbonate solution through the vertical hose for R_1 and R_2. The capacitor bank at the right is the ballast capacitance or C_2.

Table II. Effect of Wave Shape on Impulse Strength (Volts Per Mil)

	Generator 1—1x10 Wave			Generator 2—1.5x40 Wave		
	Average	Maximum	Minimum	Average	Maximum	Minimum
Cambric	1,050	1,120	1,000	1,090	1,150	1,050
Rubber	1,080	1,300	900	1,070	1,240	915

Effect of Wave Shape on Impulse Strength

These tests were made on five-foot adjacent samples taken from two lengths of single-conductor cable, number 6 solid, $^6/_{64}$-inch wall of insulation, lead sheath, one length insulated with rubber and one with varnished cambric. In table II are the results in volts per mil wall, the average, maximum, and minimum of five tests. Samples from both lengths were tested with each of two different impulse wave shapes, 1x10 and 1.5x40.

The results show no definite difference in strength between the two wave shapes in spite of the considerable difference in shape. One wave is 50 per cent slower than the other on the front and four times longer than the other on the tail. This lack of a real difference in strength between the two waves is good evidence that a reasonable deviation in our wave shape from the calculated should have no appreciable influence on the test results, and therefore that the lack of an oscillograph should not seriously limit the value of the test results.

This lack of difference also indicates that any conclusion based on either shape should hold for the other shape and for a fairly large range of impulses occurring in actual service.

Effect of Impulse Polarity on Impulse Strength

Table III shows the effect of impulse polarity on the impulse strength of three

Table III. Effect of Impulse Polarity on Impulse Strength of Rubber-Insulated Wire

Wire Size	Insulation Wall	Impulse Polarity	Impulse Strength in Volts Per Mil			Ratio, Positive/Negative (Average)
			Average	Maximum	Minimum	
No. 6 solid	$^9/_{64}$-inch	Positive	1,033	1,150	900	0.84
		Negative	1,225	1,300	1,200	
No. 6 solid	$^{10}/_{64}$-inch	Positive	1,400	1,550	1,250	1.09
		Negative	1,290	1,450	1,150	
No. 6 solid	$^{14}/_{64}$-inch	Positive	928	1,050	780	1.02
		Negative	905	1,000	850	

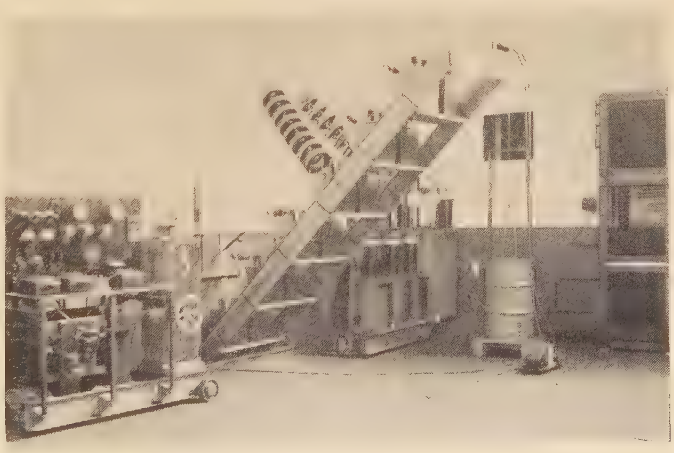

Figure 2. Generator 2

Table IV. Effect of Electrode Surface on Impulse Strength (Volts Per Mil)

	Average	Maximum	Minimum
Lead sheath	1,400	1,490	1,300
Rubber surface in 0.1 per cent salt water	1,390	1,440	1,300
Lead foil wrapped around rubber insulation	1,410	1,480	1,340

different sizes of rubber-insulated wire. The tests were made on five-foot samples with generator 1 and the 1x10 wave.

On the average no real difference in strength is indicated between the two polarities. Unless specified otherwise all other tests reported in this paper were made with the negative polarity.

Impulse Strength of Rubber-Insulated Wire—Effect of Electrode Surface

Table IV gives the results of tests made on five-foot samples of number 6 solid, $^{6}/_{64}$-inch wall of rubber, using three different kinds of outer electrode surface. All tests were made on generator 2 with the 1.5x40 wave. The results are in volts per mil wall, average, maximum, and minimum of at least five tests.

These results show that any one of these types of outer electrode can be used indiscriminately. In most cases the salt water is most convenient for testing rubber-insulated wire.

Impulse Strength of Rubber-Insulated Wire—Effect of Specimen Length

All samples used for these tests were taken from the same length of wire, single conductor number 6 solid, $^{6}/_{64}$-inch wall of 60 per cent high-voltage rubber compound, tape, and lead sheath. Generator 2 was used with the 1.5x40 wave. Table V gives the test results in volts per mil of wall.

The results in table V indicate no effect of sample length on the impulse strength of the wire, while the 60-cycle strength of the same wire decreases with increasing sample length at about the usual rate. We have seen this unexpected tendency of the impulse strength in other of our test results but plan to investigate it further before accepting it as conclusive. There has been no tendency for the faults in the longer samples to be located near the sample ends. Different arrangements of the longer samples have been tried without finding any consistent effect. Without a cathode-ray oscillograph we have been unable to determine the effect of the sample capacitance on the wave shape, but in view of the results in table II we doubt that this effect is sufficient to affect the impulse strength.

The ratios of impulse to 60-cycle strength in table V are seen to be considerably lower than those in table VII because the rather high 60-cycle strength of the table V wire is not accompanied by abnormally high impulse strength. That is, the impulse strength does not seem to have any fixed relation with the 60-cycle strength. On five-foot samples the ratio may vary from two to four.

Impulse Strength of Rubber-Insulated Wire—Effect of Insulation Thickness

These tests were made on five-foot samples of rubber-insulated wire in salt water, using generator 1 with the 1x10 wave. Five samples were tested at each of seven different wall thicknesses between $^{5}/_{64}$ and $^{22}/_{64}$ inches, on a number 6 conductor or thereabouts. All insulating walls were 60 per cent rubber but of slightly different types. For this reason the actual results gave a rather irregular plot versus wall thickness. The results given in table VI represent a smooth curve averaging the actual results. Therefore, although the reported results are subject to some variation, they represent the trend or general effect of thickness on the impulse strength of 60 per cent rubber insulation on a number 6 conductor.

In table VI these average results of unit impulse strength decrease with increasing wall thickness. The same tendency has been shown by the a-c strength of many insulations.

Table V. Impulse Strength of Rubber-Insulated Wire—Effect of Specimen Length

Specimen Length (Feet)	Specimen Capacitance (μf)	Impulse Strength (Volts Per Mil) Average	Impulse Strength Maximum	Impulse Strength Minimum	60-Cycle Strength (Volts Per Mil)* Average	60-Cycle Maximum	60-Cycle Minimum	Ratio, Impulse to 60 Cycle (Average)
1	0.00006	1,050	1,230	900	580	690	510	1.8
2	0.00012	1,120	1,260	960	550	590	500	2.0
5	0.0003	1,117	1,240	920	496	550	420	2.2
10	0.0006	1,231	1,380	1,020	470	520	430	2.6
20	0.0012	1,130	1,340	920	440	490	400	2.7
40	0.0024	1,128	1,330	925	415	510	380	2.7

* All 60-cycle strengths given in this or other tables are effective and not peak.

Table VI. Effect of Wall Thickness on Impulse Strength of Rubber-Insulated Wire

Insulation Wall in 64ths Inch	Impulse Strength in Volts Per Mil
5	1,400
10	1,150
15	970
20	800

Impulse Strength of Rubber-Insulated Wire—Effect of Compound Type

It is well known that there are many different types of rubber cable insulation and that they may differ considerably in their properties. Each type is designed and used for a particular kind of service. The results of table VII are given to show the effect of the rubber compound type on the impulse strength and the ratio between that strength and the 60-cycle dielectric strength.

All samples were five-foot active, number 6 or number 8 with $^{5}/_{64}$-inch or $^{6}/_{64}$-inch wall, tested in salt water on generator 2 with the 1.5x40 wave. The results are in volts per mil wall.

The results in table VII indicate at least general correlation between the impulse and 60-cycle strengths. Because of variables in each type of compound that are outside of the present discussion, the impulse and 60-cycle strengths of each type are subject to some variation from the values given. But the results in table VII serve to give the general magnitude and to indicate that the impulse strength of rubber compounds may be as high as 1,600 volts per mil and as low as 700 volts per mil for these insulation walls. In general the impulse strength is seen to be about three times the 60-cycle strength.

Impulse Strength of Rubber-Insulated Tree Wire

These tests were made on generator 2 with the 1.5x40 wave, using five-foot samples of number 6 solid, $^{5}/_{64}$-inch wall of rubber, braid, with and without fiber

tape under the braid, dry and after soaking in water for 20 hours. The dry tests were made with lead foil wrapped over the wire and those after soaking were made in water. Each result given in table VIII is the average of at least five tests on adjacent samples. The 60-cycle tests were made by increasing the voltage three kv per 15 seconds.

The impulse strength of this type of wire is particularly important because the wire is directly exposed to lightning and the insulation wall is seldom more than $^8/_{64}$ inch. In table VIII the impulse strength is seen to be generally typical for that rubber wall. The differences between the two types of wire are not enough to indicate that the fiber tape is of any real value as insulation, especially when the wire is wet.

Table IX. Impulse Strength of Cable—Rubber Versus Cambric Versus Paper

Insulation	Impulse Strength (Volts Per Mil) Average	Maximum	Minimum	60-Cycle Strength (Volts Per Mil) Average	Maximum	Minimum	Ratio, Impulse to 60 Cycle (Average)
Anhydrex rubber	1,143	1,300	900	350	400	310	3.3
Cambric	1,040	1,100	1,000	300	360	250	3.5
Paper	1,920	2,000	1,770	540	570	520	3.6

Table X. Impulse Strength of Sheets—Rubber Versus Cambric Versus Paper

Insulation	Impulse Strength (Volts Per Mil) Average	Maximum	Minimum	60-Cycle Strength (Volts Per Mil) Average	Maximum	Minimum	Ratio, Impulse to 60 Cycle (Average)
Paper—two layers	3,890	4,400	3,550	1,600*	1,900	1,480	2.4
Cambric—two layers	3,630	4,000	3,200	1,400*	1,590	1,220	2.6
Rubber—one layer	1,993	2,500	1,200	750*	960	600	2.7

* One layer.

Relative Impulse Strength of Rubber, Cambric, and Paper-Insulated Cable

All tests were made on the same size cable, number 6, $^6/_{64}$-inch wall insulation, lead sheath. The rubber was a typical 60 per cent, the black varnished cambric was typical of the best available four years ago, and the paper was kraft of about 300 seconds Gurley air resistance saturated with a typical oil used for the solid type of paper cable. Generator 1 was used with the 1x10 wave. The results in volts per mil wall are given in table IX.

The impulse strength of the paper is nearly double that of the rubber and cambric but it is interesting to note that here again as in table VII there is good correlation between impulse and 60-cycle strength. The insulations of high 60-cycle strength show correspondingly high impulse strength.

Although the impulse strength of the rubber in table IX is 40 per cent less than that of the paper, one of the rubber compounds in table VII is only 17 per cent less than the paper in table IX. Since the 60-cycle strength of the best rubber compound in table VII does not represent the highest obtainable with rubber, this suggests that it might be possible to make rubber compounds that are equal to paper in impulse strength. Because of the compounding variables the dielectric strength of rubber is subject to control over a much wider range than that of either cambric or paper.

Table VII. Impulse Strength of Different Rubber Compounds

Compound	Impulse Strength (Volts Per Mil) Average	Maximum	Minimum	60-Cycle Strength (Volts Per Mil) Average	Maximum	Minimum	Ratio, Impulse to 60 Cycle (Average)
Code	880	920	840	315	320	310	2.8
AO	870	990	690	255	260	250	3.4
Ozone resistant	1,090	1,290	920	359	400	290	3.0
Performite	740	830	700	275	280	270	2.7
AA-35	840	970	700	347	360	320	2.5
60 per cent S. C.	1,137	1,500	710	375	450	300	3.0
60 per cent H. V.	1,600	1,665	1,535	470	510	430	3.4
Anhydrex	1,340	1,460	1,360	338	365	320	4.0

Table VIII. Impulse Strength of Rubber-Insulated Tree Wire

	Average Impulse Strength, Dry, Kv	Dry, Volts Per Mil	Wet, Kv	Wet, Volts Per Mil	Average Wet 60-Cycle Strength, Kv	Volts Per Mil	Wet Ratio, Impulse to 60 Cycle
Fiber tape	107	1,370	89	1,140	24.4	313	3.6
No fiber tape	96	1,230	86	1,100	22.3	286	3.8

Impulse Strength of Rubber, Cambric, and Paper Sheets

All tests were made between two-inch-diameter brass electrodes with rounded edges, using generator 1 with the 1x10 wave. The paper was kraft of about 2,000 seconds Gurley air resistance, in layers of 0.005 inch, saturated in paper-cable oil. The varnished cambric was in 0.012-inch layers of the same type as that in table IX. The rubber was 60 per cent in 0.050-inch layers. The test results in volts per mil are given in table X.

As would be expected these results are seen to be considerably higher than those on the insulations in cable form. The strength of the sheet rubber is some 50 per cent higher than that of the thinner rubber cables tested. Similar to the cable insulation the paper sheet strength is about double that of the rubber sheet, but unlike the cable insulation the sheet cambric strength is nearly as high as the paper sheet. On sheets the ratio of the impulse strength to the 60-cycle strength is seen to be about 2.6.

Properties of Impulse Faults in Rubber and Cambric Insulation

The above results indicate that in most cases the impulse strength of rubber is in general as high as that of cambric. This does not agree with our general experience that rubber is somewhat more subject to lightning damage in service than is cambric. For this reason we made a few comparisons of the proper-

Table XI. Properties of Impulse Faults in Rubber and Cambric Insulation

	Rubber Sample	Cambric Sample
Sample 1		
15 kv d-c for 15 min	OK	OK
165-kv impulse	Failure	Failure
3 kv a-c for $1^1/_2$ hours	OK	OK
D-c dielectric strength* (kv)	6.2	10.1
A-c dielectric strength (kv)	3.8	5.2
Sample 2		
165-kv impulse	Failure	Failure
A-c dielectric strength (kv)	4.3	5.8
Sample 3		
A-c dielectric strength (kv)	45 (480 volts per mil)	31 (290 volts per mil)

* One-fifth-ampere fuse.

Table XII. Low-Energy Impulse Faults in Rubber

Sample 1

Impulse failure at 70 kv. No flash but glass broken
No location with magnifying glass
OK on 1,000-volt Megger
Fault picked up at 4 kv d-c by 0.6-milliampere kenotron
Fault less than 0.5 millimeter in diameter

Sample 2

Impulse failure at 60 kv
Fault located to within two inches by aid of flash
No location with magnifying glass
Fault picked up at 3.4 kv d-c by 0.6-milliampere kenotron
Fault less than 0.1 millimeter in diameter

ties of these faults in the two types of insulation.

The tests reported in table XI were made on two-foot samples of number 6 solid, $^6/_{64}$-inch wall of insulation lead sheath. The impulse tests were made on generator 1 with the 1x10 wave.

As shown in table XI both number 1 samples withstood 15 kv direct current for 15 minutes without failure but failed when subjected to a 165-kv impulse. After this both samples withstood 3 kv alternating current for 1.5 hours without failure, when they were removed from test. Since this voltage is more than double the operating voltage of each cable it shows that both faults would have remained in service for a considerable period after the impulse failure. Finally each fault was broken down with direct current. Although this test was made with a one-fifth-ampere fuse in series with the sample each fault was burned out to some extent. In spite of this burning each fault showed an a-c strength more than twice the operating voltage. It is interesting to note that the cambric fault gave considerably higher dielectric strength on both the d-c and a-c breakdown tests. That is, both faults would have withstood the operating voltage for some time after the impulse failure, possibly indefinitely, but the cambric fault was less likely to cause a service failure than the rubber fault. The tests on the number 2 samples confirm this comparison.

This indicates that an impulse fault in cambric is less likely to cause a service failure than one in rubber but that in either insulation the impulse failure may not cause a service failure for days, months, or even years after the impulse failure. In confirmation of this we have found lightning faults in rubber-insulated cable that was taken from service after a perfect operating record. The presence of water undoubtedly would increase the probability of an impulse fault failing in service; that is, the cable may fail during the first rainstorm after the lightning, or it may never fail.

Incidentally, these tests bring out one advantage of high-voltage d-c testing. It is a most effective means of developing any lightning faults that may be in the cable.

Table XII gives additional data to indicate the small size of a low-energy impulse fault. Each sample was one foot of number 1 4,$^3/_{64}$-inch wall of rubber, tested under water in a glass jar, using generator 1 and the 1x10 wave.

The results show that the size of such a fault may be extremely small, too small to be visible on the outside surface of the rubber. Even after being burned out by the kenotron the faults were very difficult to locate visually.

Conclusions

Within the limits of the tests made, the following conclusions appear justifiable:

1. The impuse strength of cable insulation is not critically affected by the shape or polarity of the impulse, the type of outer electrode, or the length of the specimen.

2. In walls of $^6/_{64}$ inch or thereabouts the impulse strength of rubber-insulated cable may be from 700 to 1,600 volts per mil depending on the type of rubber compound. The strength decreases with increasing wall.

3. The impulse strengths of varnished-cambric and oil-paper insulated cables are about 1,000 and 2,000 volts per mil respectively.

4. The impulse strength of cambric and oil paper insulated cable is between three and four times the 60-cycle strength but that of rubber-insulated cable may be anything from two to four times the 60-cycle strength.

5. In sheets between two-inch disks the impulse strength of rubber is some 50 per cent higher than that of rubber cable insulation of the same wall. Similar to cable insulation the sheet paper is about double the sheet rubber but unlike cable insulation the sheet cambric is nearly as high as the paper.

6. The fiber tape and braid in rubber-insulated tree wire do not add appreciably to the dielectric strength impulse or 60 cycles of the wire, particularly when wet.

7. An impulse fault in cambric insulation has higher a-c strength than one in rubber insulation but the a-c strength of either fault may be sufficient to withstand the operating voltage for long periods of time.

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Discussion

R. B. McKinley (nonmember; General Electric Company, Schenectady, N. Y.): We have also made some impulse tests on rubber insulation. Most of these were on 30 per cent and ozone-resisting compounds.

Our test results were in agreement with those presented by Messrs. Davis and Eddy in the fact that the impulse strength in volts

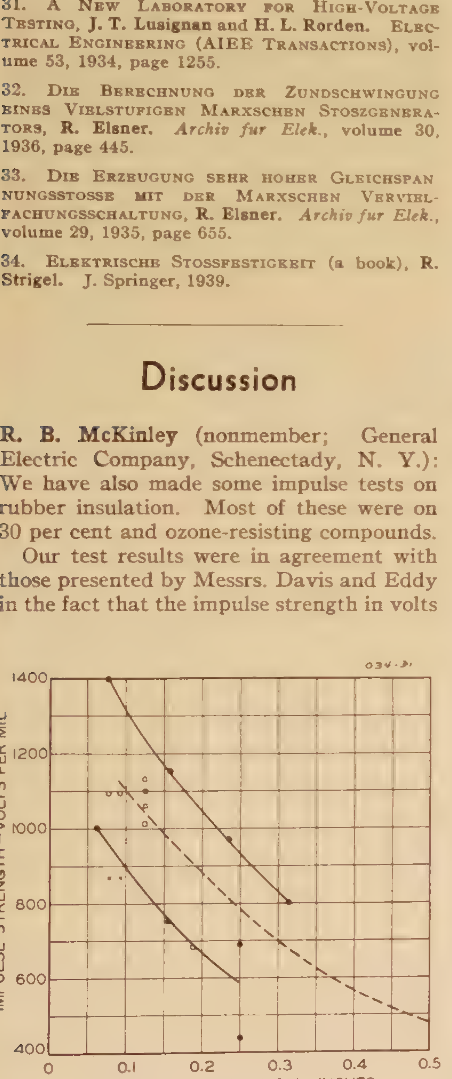

Figure 1

per mil decrease rather rapidly with increasing wall thickness. Some of the answer for this might be due to the mechanics of manufacture in that it is more difficult to hold the heavy insulation walls perfectly centered during the vulcanization period, although this was checked carefully and the fact that there might be greater difference in the degree of "cure" throughout the insulation wall. That the degree of vulcanization does have some effect is indicated by a few tests we have made.

Our values, together with some of those reported in the Davis and Eddy paper, have been plotted, and I believe the chart is worthy of a little study, as it might offer an additional reason why general experience indicates that rubber is more subject to lightning damage than varnished cambric. Furthermore, it might also indicate the advisability of further study before adopting rubber insulation for voltages in the range from 22 to 35 kv in places exposed to severe surges.

The upper curve of figure 1 of this discussion was drawn from values given in table VI of the Davis and Eddy paper. The lower solid curve shows our results obtained on 30 per cent insulation. It is interesting to note how closely the two curves parallel each other throughout the range of thicknesses tested. The points marked by crosses were taken from table VII for 30 per cent class *AO* rubber and indicate how closely the tests agree.

The points indicated by circles or squares are those for the ozone-resisting or oil-base compounds, including insulations of various manufacturers. I have drawn the dotted curve in parallel to the other two curves and extrapolated to one-half-inch insulation thickness merely to investigate what the possibilities might be at the higher voltages. The true curve for ozone-resisting insulations might of course be much different from the dotted curves shown, although the small amount of information that we do have does indicate that these insulations also have lowered impulse strength with increased thickness.

I have calculated the breakdown voltages for 26-kv cable with varnished cambric, paper, and oil-base insulations. The thicknesses of insulation for 26-kv grounded neutral for the three insulations would be 0.422 inch, 0.297 inch, and 0.469 inch, respectively. Using 1,040 volts per mil for the varnished-cambric insulation in accordance with the Davis and Eddy results, 1,600 volts per mil in accordance with the Foust and Scott paper, and 500 volts for the oil-base insulation as indicated by the extrapolated curve, the following values would be obtained:

Varnished cambric	439 kv
Paper	475 kv
Ozone-resisting	235 kv

I do not want to leave the impression that I am saying rubber insulation will not operate at 26 kv. There are cases in service to disprove that, but I do believe the results given in this paper show us something that bears looking into further before we extend the use of high-voltage rubber too rapidly.

C. M. Foust (General Electric Company, Schenectady, N. Y.): The work reported by Messrs. Davis and Eddy is interesting and valuable. On several occasions I have conducted similar tests on impulse breakdown strength of rubber insulation and have reached conclusions in agreement with the authors on most points. My general level of voltages and gradients for various wall thicknesses agrees with the figures given in the several tables of the paper and breakdown gradients decreased with increasing thicknesses as shown in table VI.

I am puzzled by the results shown in table V on the effect of specimen length. In view of the variation in breakdown between samples at any one specimen length, it seems reasonable that the impulse strength for the longer specimens should decrease as the 60-cycle values do. It is a little disconcerting to have the impulse 60-cycle breakdown ratio vary with specimen length. I am wondering if in some of the tests described an appreciable portion of the output voltage of the generator might not have been across the ground-electrode water resistance, particularly for the longer test pieces of high capacitance. At a breakdown voltage of 90 kv reached uniformly in one microsecond across a capacitance of 0.0024 microfarad, the current through the water would be about 200 amperes. At anything less than, say, ten ohms, this would be inconsequential. However, at higher resistances an appreciable resistance voltage would be obtained, resulting in reduced voltage across the insulation particularly for breakdown values occurring before crest.

Our tests using the cathode-ray oscillograph with the viewing and recording each applied wave showed breakdown to be occurring before or on the wave crest. In many cases final breakdown indicated by the chopping of the wave, occurred substantially below the previously applied crest-voltage level and on the rising front. When these actual chopped wave values are taken a breakdown-voltage value some ten per cent below the full-wave value is obtained.

In my test only one voltage wave was applied at each level while the authors applied two. Indications of occasional damage without breakdown suggest that some five applications at each level would provide a more representative breakdown value.

The authors have described tests wherein successive applications of direct, impulse, and direct voltage were applied with the conclusions derived therefrom that a cable having an impulse breakdown may remain in service for some time. However, in service the normal excitation would usually be on at the time of impulse failure and immediate follow-up of short-circuit current would certainly result in many cases.

Herman Halperin (Commonwealth Edison Company, Chicago, Ill.): Information on the surge breakdown strength of insulated power cables has been rather meager, and so the data on a variety of insulations from Davis and Eddy and on impregnated-paper insulation from Foust and Scott are quite welcome. In general, data on surge strengths of various insulations have been appearing in relatively good quantity in recent years in this country and abroad, particularly at the Paris meetings of the International High-Tension Conference.

Troubles in cables due to lightning have been pretty much confined to the lower-voltage cables connected to overhead systems. Dielectric strength to withstand surges, either due to switching or due to

lightning, may, however, be the limiting factor in determining minimum safe insulation thicknesses for the higher types of insulation in extra-high-voltage cable. Surge strength to withstand switching surges was a factor, for example, when in Chicago we adopted, in 1935, oil-filled insulation of 315 mils thickness for the 100,000-kva 66-kv lines, whereas with the solid-type 66-kv cable with about 688 mils of insulation the surge strength was greatly in excess of requirements.

The industry would, I believe, be interested in data obtained by others similar to the data on a number of variables obtained by Davis and Eddy, since such data are comparatively rare.

The rest of this discussion applies to impregnated-paper insulation for particularly power cables.

The average surge strength of 1,600 volts per mil found by Foust and Scott agrees reasonably well with the results of Held and Leichsenring[1] who reported 1,770 to 2,400 volts per mil average surge breakdown stress and with the average value of 1,920 volts per mil given in the paper by Davis and Eddy presented at this convention.

Some discrepancies between the results of various investigators probably are due to the effects of different variables which have not been well established as yet. It appears, for example, that higher breakdown values are obtained with small laboratory samples than with complete cables. It is gratifying, therefore, that the tests reported in the Foust-Scott paper were all made on complete cables. In a 1933 AIEE paper, Mr. Scott reported the results of surge tests on 15 mils of impregnated-paper insulation between flat electrodes. The surge strength for these samples was about 3,400 volts per mil. J. Borel[2] reported last year results of surge tests on small laboratory samples with concentric electrodes and insulation thicknesses of 40 to 160 mils. He obtained surge breakdowns at a maximum stress of about 2,900 volts per mil and an average stress of about 2,500 volts per mil. Also the results of Davis and Eddy confirm the conclusion that much higher surge strength values are obtained for small laboratory samples than for complete cables. They report for the former an average impulse strength of 3,890 volts per mil as compared with 1,920 volts per mil for the complete cables.

The relative surge strength of various types of cable still seems somewhat indefinite, even after considering the two papers. In a paper by Buss and Vogel,[3] published in 1935, the following tentative values were given: solid-type cable, 2,540 volts per mil; oil-filled cable, 2,000 to 2,540 volts per mil; pressure cable, 2,540 to 3,000 volts per mil. While these results indicate higher surge strength of pressure cable than for solid-type or oil-filled cables, Mr. Scott stated in his 1933 AIEE paper that "at power frequencies and under long time application of voltage there is a considerable increase in endurance strength of oil-treated insulation at pressures of several atmospheres. Under impulse stresses, however, practically no benefit is derived from increasing pressure. The effect of pressure on dielectric strength is greater the longer the time of voltage application, being negligible for the impulse voltage tests of only a few microseconds duration." On the other hand, Borel found an increase in surge strength with increasing pressure.

Other questions of interest are the effect of thoroughness of impregnation and of aging on the surge strength of cables, the cumulative effect, if any, of repeated surges, the surge strength of three-conductor belted cables as compared with single-conductor cables, and the shape of the time-lag curve. It is realized that tests of this type are cumbersome, and progress in answering these questions will be of necessity slow.

It is noted that all tests were made by Foust and Scott with positive polarity and most tests by Davis and Eddy were with negative polarity. Held and Leichsenring found no effect of the polarity on oil-filled cables but for solid-type cables obtained 5 to 13 per cent higher surge strength for positive waves than for negative waves. The higher lightning voltages are usually negative.

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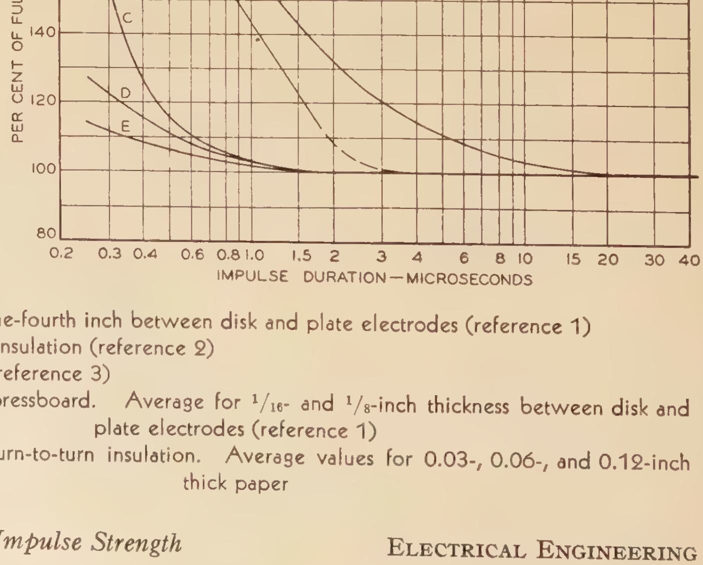
P. L. Bellaschi and **W. L. Teague** (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): These papers by Foust and Scott and Davis and Eddy present interesting data on the impulse and 60-cycle strength of insulating materials particularly those used in cables. In testing similar materials and parts and in our experience with the various factors affecting insulation breakdown, we have obtained results which are, on the whole and in principle, in accordance with the findings so ably reported in the papers by Messrs. Davis and Eddy and by Messrs. Foust and Scott. It would lead the discussion too far afield with perhaps no particular profit to attempt a minute comparison of the various findings.

There is a pertinent point which has a practical and a fundamental bearing on the insulation problem. Both papers indicate a volt-time characteristic for the type of insulation tested which is essentially constant down to one or two microseconds. These are in effect the shortest times to which the investigations were carried. The curves of figure 2 of this discussion enlarge on this fundamental question. These curves present the volt-time characteristics of liquid and solid insulation, and of apparatus insulation from the long times down to the very short impulses of 0.25-microsecond duration.

Curve A is the characteristic for transformer oil between a disk and a plate; curve D is for oil impregnated pressboard for the same electrode arrangement.[1] Curve B is the volt-time characteristic of major transformer insulation as applied to high-voltage design.[2] Curve E is for turn-to-turn oil-impregnated paper insulation. Curves D and E are also typical for other insulation, as varnished cloth, etc. While we have no data at this moment on the impulse characteristic for rubber at the very short times, there are no good reasons to suspect that it has a greater upturn at the very short times than in these last two curves.

The degree of the upturn of the volt-time characteristic depends on a number of factors, as the relative amount of liquid and solid insulation which make up the insulation body or structure, the treatment applied to the insulation, the electrode arrangement and insulation of the electrode proper, etc.

Figure 2. Volt-time characteristics of insulation



A—Transformer oil, one-fourth inch between disk and plate electrodes (reference 1)

B—Transformer major insulation (reference 2)

C—Oil-filled cables (reference 3)

D—Oil-impregnated pressboard. Average for 1/16- and 1/8-inch thickness between disk and plate electrodes (reference 1)

E—Oil-impregnated turn-to-turn insulation. Average values for 0.03-, 0.06-, and 0.12-inch thick paper

Curves A, D, and E apply for repeated applications, which consist usually from 15 to 30 impulses being applied before the point of breakdown is reached. Curve B is an endurance curve for hundreds of applications.

Curve C (from the test data on cables by Held and Leichsenring) was established from single applications. On the flat part, repeated applications gave voltage values not more than five to ten per cent lower. It is possible that the upturn at the very short times would be lower on repeated applications and that the curve would come nearer to D. There are, however, other factors which may account for the substantial upturn of curve C, as the presence of oil in relatively good amount in an oil cable. The results of Held and Leichsenring at the longer times apparently differ in one respect from those of Messrs. Foust and Scott, in that the former found the breakdown gradient at the conductor to be a constant.

The additional data on the dielectric strength of cable insulating materials, presented in these two papers, should make it possible to better tie in the relative strength and characteristics of various apparatus, and to this additional extent, give further scope and strength to the general problem of insulation co-ordination.

References

1. Dielectric Strength of Transformer Insulation, **P. L. Bellaschi** and **W. L. Teague**. Electrical Engineering (AIEE Transactions), volume 56, page 164.

2. Vacuum Boost Insulation Strength of Transformers, **P. L. Bellaschi** and **F. J. Vogel**. *Electric World*, January 1939.

3. The Behavior of High-Tension Cable Installations Under the Effect of Voltage Impulses, **Ch. Held** and **H. W. Leichsenring**. Paper number 207, C.I.G.R.E., Paris, June–July 1939.

L. G. Smith (Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md.): The industry is indebted to the authors for the data contained in the papers by Foust and Scott and Davis and Eddy. We have impulse flashover strength of line and station insulators and have available impulse levels of transformers and other apparatus. These data for cable augment the information necessary to design the system insulation levels and lightning protection installations. The impulse breakdown values reported presumably are for new cable. While information for new insulation is a necessary step, the user is also interested in similar data for older cable, after voids have formed, the oil deteriorated, or some "tracking" has occurred in paper cable; the rubber has aged in rubber-insulated cable; or the insulation has deteriorated in varnished-cambric cable. Lightning protection must be designed to protect the cable throughout its useful life. It is realized that obtaining the data presented in the papers involved considerable time and expense; and that the testing necessary to establish impulse strength of insulation as it ages represents even greater costs. However, the suggestion is made at this time as a guide to further research.

In interpreting the data on paper cable, the conclusion is reached that insulation thickness and conductor size has slight effect upon the impulse strength. On the other hand, the insulation thickness appears to have a material effect upon the impulse breakdown of rubber cable. It would be of value to determine the effect of conductor size on both rubber and varnished-cambric insulated cable and the effect of insulation thickness on varnished cambric cable.

It is interesting to note that the type of rubber compound that supposedly possesses the best aging characteristics developed the lowest impulse breakdown. The statement made in the Davis and Eddy paper that an impulse breakdown of rubber or varnished-cambric insulated cable may not result in a service failure is questioned. The 60-cycle tests were made subsequent to impulse breakdown. If normal rated 60-cycle potential had been connected to the cable at the time of the impulse test, it is believed that power follow current would have reduced the fault resistance to the point where normal voltage could not have been withstood.

L. F. Hickernell (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): This paper is a valuable contribution to the knowledge of the electrical characteristics of insulated power cables in that it presents, for the first time before the AIEE, impulse-strength data on varnished-cambric and rubber cable insulation. Previous and accompanying papers have been confined to similar data on impregnated-paper insulation. ("Traveling-Wave Voltages in Cables" by H. G. Brinton, F. H. Buller, and W. J. Rudge, AIEE Transactions, March 1933, page 121, figure 7, and "Some Impulse-Voltage Breakdown Tests on Oil-Treated Paper-Insulated Cables" by C. M. Foust and J. A. Scott, AIEE Transactions, volume 59, 1940, pages 389–91.)

Impulse Generators

Referring to "Impulse Generators", it is stated the *impulse* voltage was applied in seven-kv steps. Referring to "Impulse Strength of Rubber-Insulated Tree Wire", it is stated that the *60-cycle* voltage was applied at the rate of three-kv per 15 seconds. In determining values of ultimate breakdown strength, the rate of rise of the applied voltage is important. Generally speaking, the faster the rate, the higher the value obtained. Accordingly, the following questions arise:

1. Were all 60-cycle breakdown tests conducted with the same rate of rise of applied voltage?

2. If so, what was the rate? (That is, does the three-kv per 15 seconds, stated under "tree wire" apply to *all* 60-cycle tests?)

If the rate of rise were three-kv per 15 seconds, it should be noted that the values in the paper cannot directly be compared with data obtained from factory test reports which generally are governed by ASTM designation $D470\text{-}37T$. Section 13 of this standard specifies a rate of rise of three-kv per second.

Effect of Electrode Surface on Impulse Strength

Table IV shows the results obtained with the following means of providing the grounded electrode:

1. Lead sheath
2. Immersion in salt water
3. Lead foil wrapped over insulation

It is concluded that the method used has no effect on the results. Inasmuch as (1) is unaffected by the time of immersion whereas (2) and (3) are, it would seem that the time of immersion prior to test was relatively short and should be so stated. In any event, the limit of the time of immersion for which this conclusion holds should be stated.

Effect of Insulation Thickness on Impulse Strength

Table VI indicates a decrease in unit impulse strength with increasing wall thickness which is the basis for the statement, "The same tendency has been shown by the a-c strength of many insulations." While it is generally true that the unit *60-cycle* strength decreases with increasing thickness, most investigators have found that the unit *impulse* strength of insulations in general is practically proportional to their thickness; or as popularly stated, "an inch is an inch" insofar as impulse strength is concerned. This has been demonstrated by many investigators for porcelain insulators and to a more limited extent for impregnated-paper insulation (see references in first paragraph). Therefore, it would seem that if the data in table VI are truly representative after confirmation, the conclusion should be confined to *rubber* insulation.

Effect of Compound Type on Impulse Strength

In table VII, the following average 60-cycle strengths are shown for three types of rubber insulation:

Rubber Compound	60-Cycle Strength (Average) Volts Per Mil
Code	315
ASTM type AO	255
Performite	275

While no claim has been made generally that type AO or Performite are high-voltage insulations, it is rather surprising to note that the authors obtain lower dielectric strength with their type AO (30 per cent) and Performite (35 per cent) than they do on their Code (20 per cent) compounds. It

Table I

Table Number	Insulation	Conductor (American Wire Gauge)	Insulation (64ths)	Outer Electrode	Impulse (Average Volts Per Mill)
VII	Anhydrex	6 or 8	5 or 6	(Salt water)	1,340
IX	Anhydrex	6	5	Lead	1,143
				Ratio =	1.17

is not believed that this is truly representative of the relative rating of these types of insulations in the industry in general.

Relative Impulse Strength of Rubber, Cambric, and Paper-Insulated Cable

Rubber. The text states these tests were conducted on a "typical 60 per cent rubber," table IX indicating this to be "Anhydrex" rubber. It would be interesting to know the reason for the lower impulse strength of Anhydrex rubber shown in table IX as compared with table VII, as shown in table I of this discussion.

Paper. It would be of interest to know the thickness of the paper tapes as well as the Gurley air resistance. It may be pointed out that 300 seconds air represents a *low* density paper as judged by modern standards of paper-cable manufacture. This paper is quite different from that used for the sheet tests reported under "Impulse Strength of Rubber, Cambric, and Paper Sheets" (five mils, 2,000 seconds Gurley).

The term "typical oil" is rather indefinite in view of the present use of naphthenic and paraffinic-base oils from different fields, with or without rosin, by the several manufacturers.

Control of Rubber. The authors suggest the possibility of making rubber insulation equal to paper in impulse strength because the "compounding variables" in rubber are subject to a wider range of control than in paper or cambric. In this endeavor, the well wishes of the entire industry will be extended to them. However, it would seem only fair to point out that both theory and present experience would indicate this to be a most difficult if not impossible assignment. In general, dielectric strength seems to follow the same laws as mechanical strength; namely, a laminated structure is stronger than a solid structure. Rubber is a more or less solid material; paper and cambric are laminated structures.

While it is true that there are more "compounding variables" in rubber than paper and cambric and hence more factors to juggle, there are also more chances for things to go wrong and the manufacture is on the whole less subject to control. A recipe for a rubber insulation will contain from five to ten ingredients compared with two for paper or cambric. The advantage of this flexibility is offset by the difficulty of controlling the quality and dispersion of so many ingredients (gum rubber itself is practically impossible to control). In addition to formulation, a rubber compound must be mixed, rested, warmed, tubed or stripped, and vulcanized. While these operations are subject to some control, the degree does not approach that capable with paper insulation. A paper cable can be closely governed by actual measurement of its electrical characteristics during its processing. Accordingly, it is doubtful if a commercial length of rubber cable can be made foot by foot of as high and uniform quality as paper cable simply because the manufacturing processes are inherently not subject to as fine a degree of control.

Properties of Impulse Faults in Rubber and Cambric Insulation

The conclusion that the 60-cycle strength of either rubber or cambric is sufficiently high after an impulse fault to prevent a *service* failure for some time is not substantiated by the test data in table XI. In actual service, a lightning fault is generally followed by a 60-cycle power arc which burns the insulation and greatly lowers the a-c strength. This service condition is not simulated in a shot from an impulse generator with no power follow-up.

E. W. Davis and W. N. Eddy: Mr. McKinley's calculated comparison of the impulse strength of 26-kv walls of varnished cambric, paper, and rubber leaves the rubber a poor third with only one-half the impulse strength of paper or cambric. We cannot agree that this comparison is justifiable, for three reasons:

1. His determination of the ozone-resistant rubber strength by extrapolation to 0.469-inch wall is too speculative with the available data limited to six points between 0.075- and 0.125-inch wall.

2. His assumption that the cambric strength at 0.422-inch wall is as high as that at 0.094-inch wall does not appear justified in the complete absence of data. Cambric may not be any more similar to paper in impulse strength than in other electrical properties.

3. For a 26-kv cable we would use a 60 per cent high-voltage rubber (with proper ozone protection) which in table VII has an impulse strength 50 per cent higher than that of the ozone-resistant rubber.

Both Mr. Foust and Mr. Hickernell question the significance of the data in table XI because the impulse faults were not produced with the 60-cycle and impulse voltages superposed as they probably would be in the field. We do not believe that this limitation is serious. Considerable data from laboratory tests on cable taken from service, from field tests on installed cable, and from customers' records indicate that impulse faults may be formed in the presence of continuously applied 60-cycle voltage and the cable still remain in service for an indefinite period after the lightning damage. A typical field experience is that the breaker opens during the storm but is immediately reclosed with no further trouble. Sometimes there is not even this indication of lightning trouble. Hours or even days after the storm the cable fails. Subsequent tests show that in addition to the developed fault causing the failure the cable often contains other faults having properties very similar to the laboratory-made impulse faults described in tables XI and XII.

Mr. Foust is puzzled by the constant impulse strength shown in table V with increasing sample length. We share his point of view. In fact we investigated the matter in more detail than is indicated in the paper and intend to continue this investigation at the first opportunity. In connection with his discussion of the voltage drop across the water the following testing details lead us to doubt that an appreciable portion of the impulse is taken by the outer cable electrode.

All water was salt water. Tests were made in water on samples from one length at one, two, five, and ten feet from another length at one, two, five, and ten feet and from another length at two and five feet. Tests were made on leaded samples (not in water) from another length at 10, 20, and 40 feet. None of these 70 tests show any appreciable effect of the length. They are all well represented by the values in table V.

With reference to Mr. Hickernell's questions, in the order given;

1. All 60-cycle breakdown tests were made with the same rate of voltage increase, three kv per 15 seconds. Our experience indicates this rate to be the most practicable in general for such purposes. We have been using it more than 12 years.

2. In connection with table IV we do not understand his statement that method 3 (lead foil wrapped over insulation) is affected by the time of immersion. Only method 2 (immersion in salt water) is affected by the time of immersion. In general our tests indicate that there is no appreciable influence of immersion time in salt water on dielectric strength for several months. Since none of the samples reported in the paper were immersed in the salt water more than one hour, we believe there is no influence of immersion time.

3. We agree that any conclusion from table VI should be limited to rubber insulation. In fact we feel that the wording of the paper makes this quite obvious.

4. With reference to table VII he questions the relative 60-cycle strengths of Code, *AO*, and Performite compounds (given as 315, 255, and 275 volts per mil respectively). Our tests indicate that these differences in dielectric strength are too small to be of any significance. These particular values were obtained on the particular wire used for the impulse tests. Hundreds of other tests made by us on these three compounds indicate no significant difference in 60-cycle strength among the three of them.

5. He questions the slight difference in the impulse strengths of Anhydrex shown in tables VII and IX. We have a good many different Anhydrex compounds. As it happens, that in table IX showing a strength of 1,143 volts per mil is one of the earlier compounds while that in table VII (1,340 volts per mil) is a more recent compound. As stated in the paper, all the tests were not made at the same time.

7. The tapes in the paper cable were three-fourths inch wide by 0.007 inch thick. The oil was paraffin-base, without rosin.

8. Without attempting a detailed discussion of the control of rubber we may say that we are unable to share Mr. Hickernell's pessimism in this respect, because we have too much evidence that the physical and electrical properties of rubber compounds can be kept under close control.

Co-ordination of Power and Communication Circuits for Low-Frequency Induction

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WHERE power and communication facilities are in proximity, electromagnetic induction from the power system may cause disturbances in the communication system. The avoidance or minimizing of such disturbances, with due regard to the service and other needs of both systems, is a problem of co-ordination, which is conveniently divided into two parts, one dealing with low-frequency inductive co-ordination and the other with noise-frequency co-ordination.

The present paper undertakes a general examination of the problem of low-frequency inductive co-ordination in the light of developments during the past decade. The situation as it existed at the beginning of the decade is to be found well set forth in a paper presented in 1931 at the AIEE winter convention by R. N. Conwell and H. S. Warren. The present paper, like its predecessor, derives from the work of the Joint Subcommittee on Development and Research* of the Edison Electric Institute and the Bell System. It is largely concerned with induction from currents due to power system ground faults and the transients which accompany such faults. It gives relatively little attention to continuous low-frequency effects since, up to the present at least, such effects have not been a primary concern in the low-frequency co-ordination of commercial power circuits and Bell System communication circuits.

A further object of the paper is to outline the various factors that require consideration in practical situations and to discuss their significance under present-day conditions. To provide necessary background for this, recapitulations of fundamentals are included at appropriate points. Detailed discussions necessarily omitted from the paper itself are to be found in the papers listed in the bibliography, many of which, particularly the Conwell-Warren paper,[1] contain further references.

A situation which calls for measures of inductive co-ordination ordinarily involves a parallelism or quasi parallelism of sections of power and communication lines. The possibility of disturbance by electromagnetic induction from the one system to the other depends upon certain characteristics of the power system (called "influence factors") and also upon such characteristics of the communication system as affect its liability to disturbance ("susceptiveness factors"). Of equal significance are the "coupling factors", which determine the electromagnetic coupling between the two systems. Figure 1 is a diagrammatic representation of the main factors of these three groups in a low-frequency induction situation. Some of these items can obviously be evaluated by calculation or by relatively simple tests, while others do not lend themselves to determination by such methods.

In a low-frequency induction problem, where, as in figure 1, power-system ground-faults are involved, it is customary, first, to calculate the maximum "open-circuit" longitudinal induced voltage. To do this, values are required for the residual power current (that is, in general, ground-return current) to produce this maximum voltage and for the corresponding coupling coefficient. The "open-circuit" voltage thus calculated is next reduced to what may be called the "shielded" maximum longitudinal induced voltage. In this reduction, allowance is made for shielding effects exerted by normally grounded paralleling conductors (ground wires, cable sheaths, etc.) and, in the case of cables, by core conductors. In addition, allowance must be made for additional shielding resulting from longitudinal currents set up in communication conductors normally free from connections to ground, but which become grounded, through protector operation, as a result of the induction. This latter allowance is not ordinarily a simple matter.

It is also usually necessary to know approximately how frequently voltages within specified ranges of magnitude will be induced, and how long they will last when they occur, since the duration of the disturbance affects the energy transferred to the communication system.

Further, although the longitudinal voltages are determining with respect to some kinds of interference, voltages to ground are important with respect to other types. Hence a certain amount of estimating of the distribution of the induced longitudinal voltages with respect to ground is generally desirable.

The final step is, of course, the estimation of the adverse effects of these voltages upon the operation and maintenance of the communication circuits, and the determination where necessary of measures to be taken in either or both systems to minimize the effects.

Valuable information regarding the fundamental factors just discussed has been secured in an analysis[2] of automatic oscillograph observations from 29 actual exposures, which also indicated sources of uncertainty in making advance appraisals of low-frequency induction situations. Comparison of maximum observed voltages with maximum estimated values showed deviations up to about 75 per cent, in both directions. Contributing to these discrepancies were shielding from telephone-line conductors grounded by protector operation, erroneous assumptions of fault resistances, failure of faults to occur at or near locations to produce the maximum voltage, and wave-shape distortion of induced voltage. Duration of induced voltage, distance between protector locations, and number of wires on the telephone line were important in cases of protector grounding. Distribution of induced longitudinal voltage with respect to ground was clearly a matter of importance, although not covered by the available data.

The several factors of influence, coupling, and susceptiveness will now be discussed in order.

Power Systems—Influence Factors

Residual Current Magnitudes—Calculation and Limitation

The magnitude of fault current and its distribution among the various branches of a network may be calculated for any

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* Referred to hereinafter as the "Joint D. & R. Subcommittee."

1. For all numbered references, see list at end of paper.

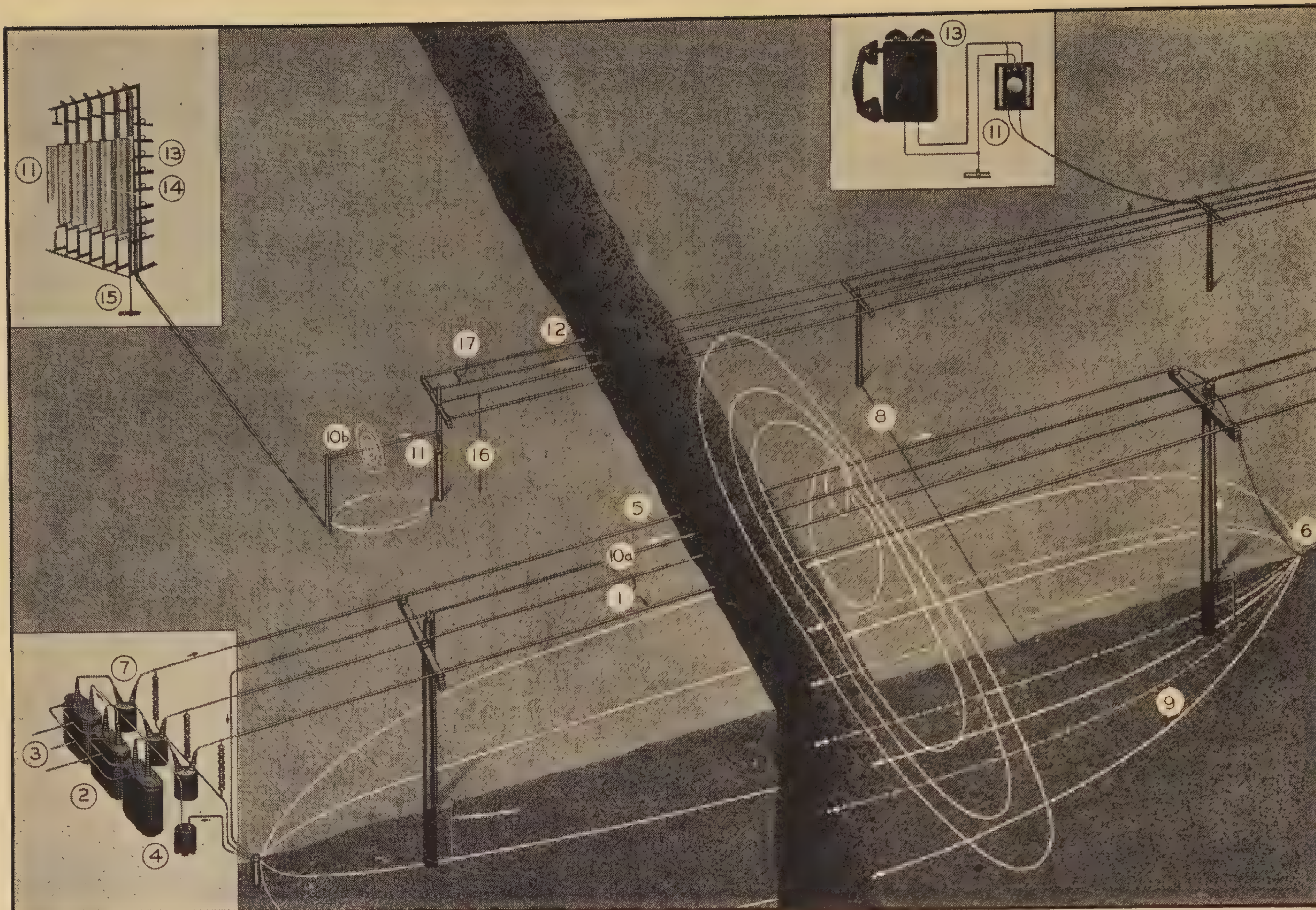


Figure 1. Factors affecting the severity of an inductive exposure

Influence Factors—Affecting magnitude and duration of power-system residual fault current:

1. Line voltage
2. Transformer impedance
3. Impedance of supply to transformers
4. Method of neutral grounding and grounding impedance if used
5. Power-line impedance
6. Fault location and fault resistance
7. Circuit breakers and tripping equipment

Factors (not indicated in drawing) affecting frequency of occurrence in faults include:

Lightning, wind, and sleet storms

Construction practices

Foreign objects in line

Coupling and Shielding Factors—Affecting induced voltage in communication system for given residual current in power system:

8. Separation between lines
9. Earth resistivity (also affects influence)

10*a*, 10*b*. Shielding from power-line ground wire and telephone-cable sheath when present

Susceptiveness Factors—Affecting communication system disturbances under given induced-voltage conditions:

11. Protectors—breakdown of blocks and rating of fuses
12. Size, length, kind, and number of wires on line (Some wires may become shielding conductors due to protector-block operation)
13. Low-frequency characteristics of equipment
14. Impedance to ground of terminal equipment
15. Resistance of ground connection
16. Voltage from conductors to ground
17. Voltage between wires (arising from differences of voltage to ground)

(Not indicated)—Location of exposure with respect to nearest protector blocks

assumed fault location and operating setup.[3] For a grounded-neutral system the fault location is usually assumed at the end of the exposure remote from the neutral ground. When line-to-ground fault current may be fed into the exposure from two directions, consideration should be given to the sequence of breaker operation in calculating the conditions for maximum induced voltage. Where ungrounded circuits are involved, it is the usual practice to assume a fault on one phase at one end of an exposure and a fault on another phase at the other end. This condition gives the maximum possible ground current through the exposure and hence the maximum induced voltage. As a rule, this current is larger than the current through the same exposure under the assumption of direct-grounded power neutral.

The impedances of power lines and cables are important elements in determining the magnitudes of residual currents under fault conditions. The most important gaps of ten years ago in data regarding these quantities have been filled in a report of the Joint D. & R. Subcommittee.[4] Impedances in power-circuit neutral-ground connections of course affect ground-fault current magnitudes. Such impedance may be inherent in the grounding equipment or may take the form of an external resistor or reactor, or a Petersen coil (ground-fault neutralizer). Considerations arising from power system design and operation affect the magnitude of neutral impedance which may be used.

In calculating ground-fault currents for use in estimates of induced voltages, significant errors may be caused by failing to take account of fault resistance. This, and other fault characteristics of interest, have been studied by the Joint D. & R. Subcommittee with the co-operation of a number of power companies.[5,6] Data were collected by means of automatic oscillographs from 11 operating power systems, having a total of about 2,800 circuit miles of transmission line at voltages ranging from

26 to 220 kv. The periods of observation were from $1^1/_4$ to $5^1/_2$ years. For one-line-to-ground faults, the most frequently occurring apparent fault-resistance, irrespective of fault location, was found to be about 20 ohms (5 ohms for faults at stations), with no great difference as between lines supported on steel structures and on wood structures. However, the studies did not include any lines designed for maximum utilization of the impulse strength of wood.

Since the installation in 1931 of two Petersen coils on a 140-kv system,[7] about 30 other Petersen coils have been installed in this country. With a given arrangement of coils, the residual current in a given exposure, and consequently the induced voltage, is practically independent of fault location. With a directly-grounded or an isolated power system, the induced voltage depends upon the relative locations of fault and exposure, and may vary over a wide percentage range. In grounded-neutral systems, residual currents large enough to make limitation desirable for inductive co-ordination purposes usually occur only where the neutral is grounded either directly or through a low impedance, and large reductions are obtainable through the employment of a Petersen coil.

Line outages preventable by Petersen coils are mainly those due to lightning flashovers. To clear faults not extinguished by the coil, recourse is usually had to short-circuiting the coil, either directly or through an impedance, and relaying out the faulty section of line. Unless a fairly high impedance is used, the residual current would usually be quite large under this condition. But the proportion of all faults that can be cleared without by-passing the coil (reported as from 70 to 90 per cent in various cases[8]) is sufficient to be of real value, even when no impedance is used in series with the by-pass breaker.

From the standpoint of inductive co-ordination, other types of neutral impedance, such as resistors, can be used for current limitation, and their status does not appear to have changed in the past ten years or so. Fault-current limitation has certain advantages from the power operating standpoint, for example, in limiting voltage dips, possible loss of load, and shock to system during faults,[7] and for improving transient stability.[9] Against these advantages, certain disadvantages have to be weighed, if the neutral impedance is to be high enough to have a large effect in most low-frequency induction cases. These questions center mainly upon dynamic overvoltage and the closely related matter of system insulation, and upon relaying.[10]

Dynamic overvoltages vary over a power system because of the flow of residual current through line impedances. In figure 2 a few results are shown from a recording oscillograph study of dynamic overvoltages on overhead systems under operating conditions.[11,12] The percentage of observed cases in which the voltage exceeded twice normal was about 64 for the isolated system, about 5 for the system grounded through Petersen coils, and about 34 for the resistance-grounded system (75 ohms). These records from operating systems were in general accord with the results of staged tests.[13] No evidence was found of the building-up of high sound-phase voltages, such as have been inferred to be possible from theoretical studies of the "arcing-ground" phenomenon. The view has recently been expressed by other investigators that such a voltage build-up is not to be expected if the arc path is between fixed contacts in open air, as in the case of an arc to ground on an overhead line, but that it may occur if the arc occurs in a confined space[14] or between breaker contacts whose separation is increasing.[14,15]

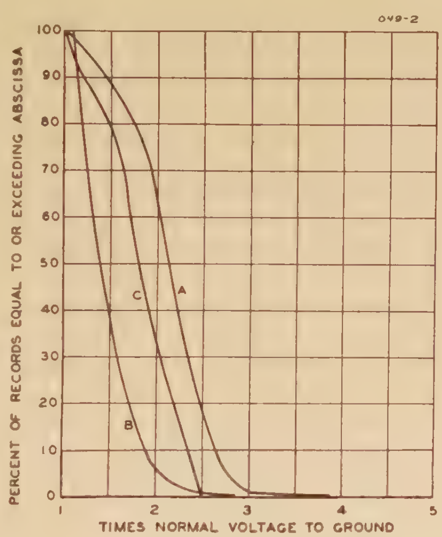


Figure 2. Dynamic overvoltages—magnetic-oscillograph observations on operating systems

A—800-mile 140-kv isolated system
B—274-mile 140-kv Petersen-coil system
C—158-mile 26-kv 75-ohm resistance-grounded system

Questions concerning system insulation[16,17,18] may arise when it is proposed to apply a relatively high neutral impedance to a system previously operated with neutral grounded directly. The nature of these questions can be indicated briefly by recalling that a lightning arrester must operate at an impulse voltage amply below the insulation level of the protected apparatus and still not operate or pass current on dynamic voltages likely to be impressed upon it by power sources in the system. While there are many factors to be considered in suiting lightning-arrester protection levels to the insulation levels of equipment, a considerable improvement during the past decade in lightning arresters, together with more detailed knowledge of their characteristics, has somewhat simplified this matter.[19]

Relaying questions involved in neutral impedance applications to systems previously operated with direct ground connections[10] include the possibility of changes in ground relays or the adoption of ground relaying if not previously used, additional potential transformers (when ground relaying is not already in use), possible changes in bushing current transformers, and in some cases, a change to a different relaying system in some portions of a network (to maintain proper selectivity). Ground relaying frequently presents difficulties for systems grounded at more than one point through high impedance.

Frequency of Occurrence and Duration of Ground Faults

The frequency with which induced voltages of various magnitudes may occur in an exposed communication system depends, first, upon the frequency of occurrence of ground faults in the power system and, second, upon their distribution with respect to the locations of exposure and power sources. In most cases, appraisals of these factors are largely matters of judgment. Valuable guidance is usually obtainable from operating experience on the power system or similar systems in the same locality, and from consideration of the character of line construction, connected line mileage, and number and location of neutral grounds. Duration of ground faults can usually be approximated well enough from relay and circuit breaker characteristics.

A simple illustration of the bearing of the relative locations of exposure and power source upon the frequency of occurrence of induced voltage is given in figure 3. In diagram (*A*) the exposure is at an unfavorable location—practically every ground fault would result in residual current through the exposure. On the other hand, an exposure located as in diagram (*B*) would be appreciably affected only by the faults between stations *B* and *C*. In diagram (*A*), it would be advan-

tageous, if practicable, to transfer the neutral ground to station (*B*). Moreover, this would not increase the number of cases of induced voltage in the exposure of diagram *B*, but would probably increase the voltages themselves.

In studies already referred to,[5,6] a large amount of data was collected regarding the characteristics of ground faults. As to frequency of occurrence there was considerable variation among systems (from 5 to 60 faults per 100 line-miles per year, averaged over the periods of observation), and also from year to year on a single system. Lightning was assigned as the known or probable cause of from 50 to over 90 per cent of the faults, depending on the system. On the average, some 10 per cent of the faults were cleared in about 10 cycles, and about 10 per cent required two seconds or more for clearance. The percentage of faults involving each of two phase wires and ground, but at different points, was small —from about one-half per cent to about six per cent in three systems for which data were available. This point is of interest in the use of neutral impedance for inductive co-ordination, since, if an exposure lies between the two fault points on different phase wires, a high induced voltage may result, the neutral impedance being ineffective for limiting ground current in this situation.

In the past ten years, the importance of direct strokes in the problem of protecting transmission lines from lightning has become fully recognized. This has led to a series of investigations which have greatly increased our knowledge of lightning,[20,21,22] and to the development of several methods of preventing interruptions to service from lightning. Measures for preventing ground faults or power follow-up after spark-over, or for limiting the duration of dynamic current to ground faults are directly helpful in low-frequency inductive co-ordination. In the remainder of this section brief comments are made on the developments that seem most significant from this point of view.

The use of ground wires on steel-tower lines results in a substantial reduction in ground faults from lightning.[23] The combined use of counterpoises and ground wires has given further improvement where tower-footing resistance or earth resistivity is high.[23,24] Where the counterpoise is continuous, it, as well as the ground wires, makes a further contribution by reducing coupling coefficients.

Possible improvements in line operation through the use of the insulating properties of wood,[25,26] while perhaps somewhat less attractive than they appeared some ten years ago, have also resulted in reduction of frequency of occurrence of faults. Quite recently renewed interest in the subject has led to a comprehensive experimental study of fundamental factors.[27]

The protector tube (expulsion protective gap), for controlling lightning flashovers on power lines, first used commer-

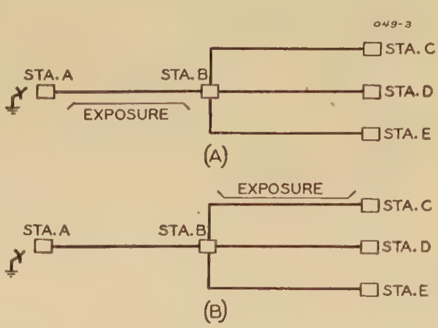


Figure 3. Relative locations of exposure and grounded sources of power—illustrative diagrams

cially in 1931–32, is finding increasing application, and has been used on lines covering the voltage range from 13.8 to 138 kv.[28,29] This device interrupts the flashover and restores the insulation within about a half cycle. It has no effect in limiting short-circuit current magnitude, and thus none in holding down the voltage induced in an exposed communication circuit. But its great rapidity of action limits the energy transferred. Because it operates directly upon the fault itself, there are no sequential circuit-breaker operations to be considered.

Another device for arc-extinction purposes is the Petersen coil. From the viewpoint of this paper, it is perhaps of more interest as a means for limitation of residual current, and has been discussed above under that heading.

Relay and circuit-breaker developments have been toward substantially higher speeds of operation, both for new installations and in the modernization of existing installations. These developments have made available breakers with an operating time of about 0.13 second, and quite recently still higher speed (about 0.085 second). These figures do not include relaying time. The exceptional speed of about 0.05 second over-all has been reached in the breakers for the Boulder Dam lines.[30,31] Like "lightning-proof" line construction and the use of expulsion gaps, high-speed breakers have, of course, no effect upon short-circuit current magnitudes. But they have the advantage of not being limited to the clearance of lightning flashovers. As used in combination with high-speed reclosing immediately following high-speed opening of circuit breakers, there will probably be some cases where fault recurrence after reclosure will diminish the inductive co-ordination benefit resulting from the high-speed opening.

From the low-frequency induction standpoint, the most notable improvements in relaying have been increases in speed of response, the further development and use of pilot-channel methods,[32,33,34] and particularly the combination of the two to replace earlier methods of selection, with much greater rapidity of relay action. In some recent applications, the time to energize the breaker trip circuit has been reduced to about one cycle (60 cycles per second) by using high-speed relays in combination with pilot channels,[35] with practically simultaneous relay operation at the two ends of the line section.

These developments in the power art, tending to reduce both the frequency of occurrence and the duration of ground faults, are all favorable to low-frequency inductive co-ordination. From a practical standpoint, the resulting degree of benefit depends upon the extent of use of these developments, and upon which are more widely used, since they are not all equally favorable. These matters, of course, are not static and the actual extent of the resulting reaction upon low-frequency inductive co-ordination is not easy to specify in quantitative terms.

Coupling and Shielding

Coupling

The residual power current, when multiplied by the coefficient of coupling between the power and telephone circuits, gives the open-circuit longitudinal induced voltage in the telephone circuit. In determining this coefficient of coupling, or mutual impedance, the telephone and power circuits are treated as ground-return circuits, regardless of normal conditions of operation as metallic circuits. Coupling coefficients can be determined as precisely as required. Methods of calculation have been considerably advanced, and in preliminary estimates, calculated values are generally used. As a rule, however, expenditures for co-ordination measures should only be made on the basis of test data or experience.

In earlier work, the calculation of coupling coefficients was based on the "equivalent ground plane" theory. This theory was first superseded by one in which ac-

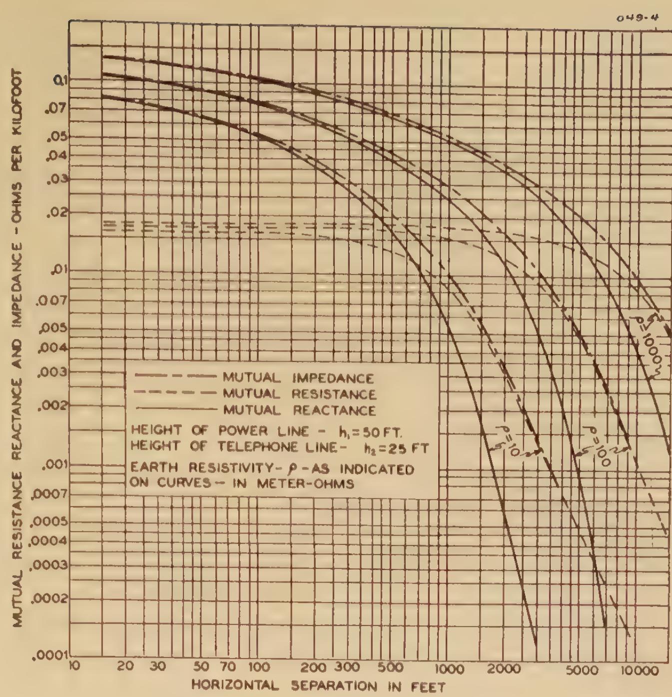
count is taken of the finite conductivity of the earth, assumed to be homogeneous. Another assumption, retained from the earlier theory, is that the primary or "disturbing" circuit is straight and of infinite length. Experimental work interpreted by this theory showed that the earth is frequently far from homogeneous and that its resistivity varies widely from place to place, from 5 to over 10,000 meter-ohms in extreme cases, with corresponding variations in coupling coefficients between circuits. This variation is much smaller at close than at wide separations. For example, at a separation of 50 feet, the 60-cycle mutual impedances between parallel circuits are about 0.36 and 0.63 ohm per mile for resistivities of 10 and 1,000 meter-ohms, respectively. At 5,000 feet separation for the same resistivities the figures are about 0.0035 and about 0.1. These relationships are shown in more detail in figure 4, which is taken from a comprehensive report[36] on coupling between ground-return circuits.

This theory has since been expanded to allow certain departures from homogeneous earth structure,[37,38,39] including a horizontally stratified earth of two layers with different resistivities. In many situations calculated values based on this assumption have agreed well with experimental results.

While the assumption of an infinitely long, straight primary circuit is satisfactory in most practical cases, there are situations in which its application is accompanied by uncertainty. Examples are where the grounding points of the power and telephone lines are in proximity at one or both ends of the exposure, and where breaks in direction occur in one or both of the circuits. Investigation of these "end-effect" phenomena have led to the development of formulas[38,39,40] in which no restrictions are placed upon the lengths of the circuits or the routes they follow, nor upon the relative locations of their end (grounding) points.

In application to practical cases, these "finite-line" formulas require a great deal more labor than the infinite-line theory. Theoretical and experimental study of the need of better precision than the latter affords has not been completed, but work done to date indicates that results based on this simpler theory need scrutiny, particularly if the earth resistivity is high, in cases of proximity of grounding points, and of breaks of direction in either circuit, toward or away from the other, and not compensated by breaks at other points in the opposite direction. If reasonably accurate knowledge of earth

Figure 4. Variation of mutual impedance with separation



resistivity is available, the effect of proximity of grounding points can be approximated by an easily calculated correction.

In "probe-wire" tests for determining earth resistivity, a number of secondaries (probe wires), parallel to a primary line and at various separations, are used. If, for some of the wires, the separations are too large compared to the length of the primary, errors in the earth resistivity, as inferred from the infinite-line formula, can be avoided by applying relatively simple corrections based upon the finite-line theory.

Earth resistivity depends on the earth structure at the location in question. A compilation of data has been made of earth resistivities in various parts of the country, including correlation of geological formation with resistivity,[41] which will serve as a general guide in preliminary estimates.

Shielding

In this discussion, the word "shielding" is used in a restricted sense to mean a reduction in an induced voltage, this reduction being caused by the action of currents brought into existence by the same primary source that causes the induced voltage. The conductors in which these currents exist are called shielding conductors or shields. They may be associated with the primary system (for example, power line ground wires) or with the secondary system, (for example, telephone cable sheaths) or they may be especially placed purely for shielding purposes. Grounded metallic structures such as water or gas pipes also frequently provide shielding. The effect of extensive networks of such pipes, as in cities, is essentially the same as a lowering of the earth resistivity, and is accounted for directly in the coupling coefficients rather than as shielding.

Results of experimental and theoretical work done on shielding by the Joint D. & R. Subcommittee up to about five years ago have been published in an engineering report.[42] Here methods and data are given for calculating shielding from conductors on open-wire telephone or power lines, from the sheaths of aerial or underground power cables, and from the sheaths of aerial or underground telephone cables with or without tape armor. An approximate method for estimating shielding from grounded-core conductors in telephone cables is included.

The information in this report shows, for example, that the shielding from a three-eighth-inch steel ground wire on a 60-cycle transmission line is 10 per cent or less; two high-conductivity aluminum-conductor steel-reinforced ground wires afford a shielding of about 55 per cent. At 60 cycles, shielding by the lead sheath of a full-size telephone cable is of the order of 50 per cent if the sheath is in good contact with the earth. When the sheath is wrapped with tape armor (two 40-mil steel tapes on the larger-size cables), this figure is increased to 80 or 90 per cent. Shielding due to power cables depends upon the construction and may vary anywhere from 40 to 70 per cent. The effects of buried pipes are usually difficult

to estimate unless the pipes are welded, because of the unknown resistance of pipe joints.

Existing methods for calculating shielding take account where necessary of distributed admittance between shielding conductors and ground. More recently, consideration has been given to the effects of currents in the disturbed conductors themselves. In long telephone cables, such currents are established in part because of the distributed admittances of the core conductors, and in part they result from the use, in normal operation, of equipment connected from conductors to ground at terminals and at intermediate repeater points. The shielding effects* of these currents, particularly those through terminal equipment, are of substantial importance. For example, considering a 50-mile repeater section of full-size cable inductively exposed, the 60-cycle voltage between conductors and ground at the terminals, where the sheath is grounded, may be only some 5 to 15 per cent of the open-circuit longitudinal voltage, that is, the induced voltage with the effects of all shielding currents, both in the sheath and in the core, eliminated. At points away from terminals, considerably larger voltages may exist between conductors and sheath and more particularly between conductors and ground, when as a result of two-directional power current feeds, shielding effects may be partially cancelled. In construction and maintenance work, a part or all of the core conductors may be open, eliminating or reducing shielding currents in them. In this case, voltages across breaks in conductors are important, as well as voltages to sheath or ground.

The usual methods for calculating reductions of longitudinal induced voltage by shielding assume in effect that in any measurements made, for example to verify the calculations, the potential of a distant ground is taken as reference. However, in cases of very close association between shielding and shielded conductors, of which cables are the best example, the voltage between these conductors (core and sheath, in a cable) is frequently of as much interest as the voltage between some point on the core and a distant point.

* From a different point of view, these effects are merely the voltage drop in the disturbed conductors, resulting, of course, from the currents set up in them by the disturbing field. This voltage drop is a self-impedance drop and the shielding is "self-shielding". When, as in the earlier discussion, the current producing the shielding is in a conductor (for example, the cable sheath) which is not itself one of the disturbed conductors, the shielding is also a voltage drop, but it is due to the *mutual* impedance between the shielding conductor and the disturbed conductors.

Questions of the character of those just discussed are on the current program of the Joint D. & R. Subcommittee. Another matter which is receiving attention is shielding by communication conductors grounded through the operation of protectors. This involves rather difficult calculations, with results liable to considerable error.

Testing Methods

Even with the advances already described in the theory of coupling between ground-return circuits, tests are generally necessary for important situations. Considerable attention has therefore been devoted to the possibilities of simplified test procedures. When lines are available for test, coupling can usually be determined most satisfactorily by a direct measurement of induction at the fundamental frequency, or by measuring the induction into short temporary ground-return circuits (probe wires). For situations in which such measurements cannot easily be made, development work on a d-c method of determining earth resistivity, using simple, readily portable apparatus has had promising preliminary results. It is expected that a report covering this and other methods will be available before long.

The development of vacuum-tube voltmeters of high sensitivity has been of value in connection with coupling measurements where one circuit is energized with a small current and the voltage induced in paralleling exploring wires is to be measured.

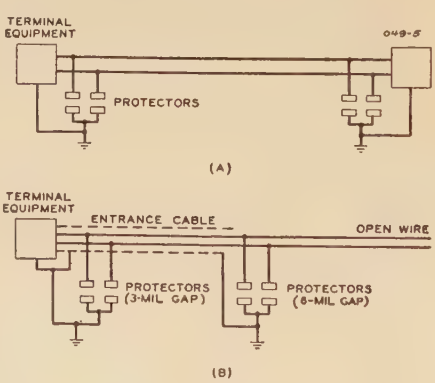


Figure 5. Diagrams to illustrate application of telephone open-space protectors

Susceptiveness

As pointed out in the Conwell-Warren paper,[1] the effects of low-frequency induction upon a communication circuit depend upon the magnitude and duration of the induction. They include service interruption due to protector operation, damage to plant, the possibility of acoustic or electric[43,44] shock, false signaling, and telegraph-signal distortion. Some of these effects, such as interference with signaling, may occur at induced voltages below the protector breakdown value. However, the more serious effects from low-frequency induction are usually associated with induced voltages sufficient to operate protectors.

An interruption to service results from permanent grounding of protectors, which occurs if the discharge current through the protector is not promptly extinguished, or if this current is very high. Protectors are employed as required for the protection of persons, equipment, or property, as at central offices, stations, etc. A simple diagram to illustrate the application is given in figure 5*A*. Where the circuit is in open wire and entrance cable is involved, an additional set of protectors is placed at the junction of the open wire and the entrance cable, as shown in figure 5*B*, to protect the cable. The protectors designed for location near terminal equipment usually consist of carbon blocks with a separation of three mils between blocks. Protectors used at the end of the cable are similar carbon blocks with about six-mil spacing. Use is also made occasionally for special purposes of a similar protector with ten-mil spacing.

The behavior of a protector of this type, particularly where the spacing is as close as three mils, depends upon a number of factors. Purely for illustrative purposes, figure 6 has been prepared from laboratory test data taken at 60 cycles. It shows the breakdown voltage distribution for a sample run of new three-mil blocks under certain specific conditions as to duration of test voltage and impedance of the test circuit. These factors, and also the number of operations to which the blocks have previously been subjected, affect the breakdown voltage characteristic as well as the ability of the protector blocks to withstand discharges without becoming short-circuited.

When induced voltages sufficiently high to break down the protectors are impressed upon the gaps on the two sides of the line to ground, there is a certain amount of dissymmetry in the resulting arc voltages across these two gaps. This sets up current through the receiver which may cause acoustic shock to the person using the receiver.

Voltages which might affect telephone linemen in the course of their work are voltages from wire to nearby grounded objects, and voltages between one wire

subject to induction and another wire grounded at nearby or distant points.

The reactions upon the subject of this paper of progress in the electrical communication art in the past decade are less direct than those of advances in the power industry, reviewed above. On the other hand, in the development of specific remedial devices for low-frequency induction situations, much has been done with regard to measures for use in communication systems. The effects of trends in the communication art and developments in communication system remedial measures will be discussed in succession.

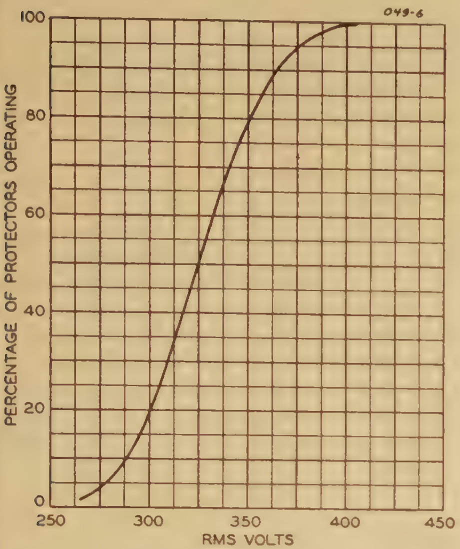


Figure 6. Breakdown characteristics of telephone open-space protectors—laboratory tests at 60 cycles

New Telephone Carrier Systems

The principal developments in wire telephone and telegraph transmission during the past few years have been toward increased use of carrier circuits.

With the availability of a system which permits the use of wider frequency bands and correspondingly more carrier channels on open-wire lines,[45] some open-wire routes can be economically developed for larger numbers of circuits instead of being replaced by cable.

In existing toll cables, the application of carrier transmission makes increases possible in the number of channels per sheath,[46] which is bringing about a tendency toward smaller physical dimensions for new toll cables. This in turn means that the shielding against low-frequency longitudinal induction would tend to be diminished unless counteracted by deliberate increases in the sheath dimensions. Shielding effects exerted on each other by cables in close proximity, which depend essentially on the total conductance of all the sheaths, would be reduced by a reduction in either the size or the number of cables.

While these developments in carrier telephony, of which the coaxial cable[47] is the most recent, present new features, principally in connection with shielding, they do not change the nature of the technical problem in an essential way. An increase in the number of communication channels per physical pair of wires, and in the number of channels along a given route, of course emphasizes the desirability of protecting the system from disturbance. However, low-frequency induction, in this respect, does not stand on a different footing from other possible sources of disturbance, aside from limitations which may be encountered in the application of specific remedial measures, such as relay protectors, to the telephone line.

Signaling

Increasing use is being made of recently developed d-c signaling systems, composited or simplexed in a manner similar to superposed telegraph, for through supervision and dialing on both local and toll trunks. These systems are provided with terminal equipment for neutralizing longitudinally induced voltage or ground potential, the functioning of which requires that it be connected to a conductor exposed to the voltage to be neutralized. For this purpose, one wire of the pair, or in the case of a phantom group, one wire of the group, is used. This normally leaves one wire for each trunk for dialing or supervision. While this arrangement reduces the susceptiveness of the system, there have been some cases in which the neutralization was apparently insufficient to take care of low-frequency induction under normal operating power-circuit conditions. This matter is under investigation.

Induction from power-system voltages under normal operating conditions sufficient to disturb grounded party-line ringers has also been experienced in some cases of exposure to rural power circuits consisting of a single phase-wire and multigrounded neutral. A ringing system has been developed, and is in some use, employing cold-cathode gas-discharge tubes to keep the circuit free of ringing grounds except when the tubes are operated, as by ringing voltage. In its present form, however, this arrangement would frequently be ineffective against induction from rural-line exposures, of the type just mentioned, since the tube operating voltages must be held within magnitudes adapted to satisfactory operation of ringing systems.

Considerable work has recently been done and is continuing on the general question of the susceptiveness of telephone equipment, particularly equipment for signaling and supervisory purposes, to low-frequency induction.

Telephone Protectors

Development work is in progress in connection with the protectors used at stations and at junctions of open-wire and cable, particularly study of the possibilities of material having a nonlinear resistance-voltage characteristic. While some of these materials appear to be valuable for special purposes, the studies have not thus far resulted in any device that seems likely to replace the present protector for general application. As has been noted in a recent paper,[48] a 3,000-volt carbon electrode gap has been developed for use as a specific measure in cases of joint use at the higher voltages.

Relay Protectors

Relay protectors installed at terminals or at the junctions of open-wire lines and cables greatly reduce the probability of permanent protector grounding, and also minimize acoustic disturbance in the communication circuits. In addition, relay protectors installed along the line minimize the possibility of electric shock to linemen by reducing potential to ground throughout the entire line. The operation of relay protectors of course results in an interruption to the communication circuits for the duration of the disturbance.

The multigrounding type of relay protector operates so as to ground all wires of a telephone line at the point where the apparatus is installed when the voltage to ground at that point rises sufficiently to operate any one of the open-space protectors associated with the installation. The discharge of current through any one or more of the open-space protectors operates a master relay, which operates the relays associated with each protector. These individual relays each short-circuit the associated protector gap and prevent permanent grounding. The improvements over the earlier equipment[49] have been (*a*) substitution of an a-c master relay, in series with a saturating transformer, for the earlier combination of rectifier and d-c relay; (*b*) speeding up of operation, which is now completed in about 0.025 second; (*c*) increase in current-carrying capacity of the short-circuiting relay contacts; (*d*) increase in

minimum release current (master relay); (e) increase in capacity of master relay to absorb heat without damage. For relatively rare situations, in which the master relay may be held up by normal induction after the power-line fault causing its operation has cleared, means may be provided for opening all the short-circuiting relay contacts after a suitable interval, these contacts reclosing quickly if the fault condition should prove not to have cleared.

In addition to this "multigrounding" type of relay protector, a "unit type", applicable to a single pair of wires only, has been developed. It is used principally at points where protectors of the ordinary type would be subject to frequent grounding and where, because the location is remote, maintenance would be delayed or expensive.

Neutralizing Transformers

Neutralizing transformers installed along a communication line provide counter electromotive forces against induced longitudinal voltages, and permit the line to operate normally through inductive disturbances. A type of transformer for neutralization on voice-frequency toll circuits has been developed and has proved satisfactory in a service trial, where 12 were used in series in two inductive exposures totaling about 50 miles in length. Each transformer is wound with 24 secondary wires. The primary, consisting of two telephone wires, is grounded at each end of the exposure and between each two consecutive transformers. This trial installation proved satisfactory both in connection with neutralizing induced voltages and in meeting the circuit transmission requirements under normal operation. Additional installations have not been made as other means have offered more economical over-all solutions of specific cases. Further development work would be required to produce a transformer adequate for circuits over which carrier frequencies are transmitted.

A unit-type neutralizing transformer, to take care of a single circuit, has also been developed. This device consists of a single primary winding with two secondary wires. Where more than a single circuit is involved, a number of units can be used with the primaries in parallel. An important application of this device is in connection with maintaining uninterrupted communication service to power stations or substations, at times of power disturbances which cause large rises in the potentials of station grounds with respect to distant points.[50] Two sizes are in use, one for 4,000 and one for 2,000 volts (60 cycles). Frequently use can be made of a cable sheath for the primary or part of it. These transformers are now in operation in a number of places.

Acoustic Disturbances

The copper-oxide rectifying element[51] has superseded the earlier combination of step-up transformer and protector gap as a means of reducing acoustic disturbances to telephone operators. Tests and operating experience have shown that the copper-oxide element is about as effective as a reducer, and has no net effective transmission loss. It is smaller and lighter than the earlier type and the indications are that it will have a satisfactory service life in use at central offices.

In circuits with telephone repeaters, the nonlinear characteristics of the vacuum tubes cause the tubes to function as devices for limiting acoustic disturbances. A study of the quantitative relationships has been made, including determination of the factors to be taken into account in order to realize as fully as practicable the power-limiting possibilities.[52]

Conclusion

The foregoing review will have shown, it is believed, that the net result of development of the past ten years has been favorable to low-frequency inductive co-ordination. Over-all improvement has in fact occurred, and has accompanied a growth in the power and telephone industries which, though less than expected ten years ago, has not been inconsiderable. It is estimated that in the decade increases in the neighborhood of 30 per cent have taken place in power generating capacity and in mileage of transmission circuit in the range from 22 to 66 kv. In the Bell System, telephone toll circuit mileage has increased some 22 per cent and telephone stations about 7 per cent.

In an important degree, the contribution of the Joint D. & R. Subcommittee to this favorable result has been due to the assistance it has received from operating power and telephone companies. This helpful relationship will, it is hoped, continue in the working out of the problems that remain and the new ones to be expected from future growth and development.

Summary

We recapitulate here principal developments of the past decade in the problem of low-frequency induction, with remarks on the resulting present status and future plans for study of different phases of the problem.

General

1. Studies of effects in actual low-frequency inductive exposures have been useful in developing general procedural methods, but have indicated the need of further work on certain items, with reference particularly to facilitating the appraisal of proposed situations in advance of construction.

Influence

2. In the calculation of residual currents, the more important gaps have been filled by the experimental determinations of the impedance of ground-faults on operating systems, and of the impedances and admittances of lines (especially cables).

3. In residual-current limitation, probably the most interesting development is the installation, within the last three years, of about 30 Petersen coils. The Petersen coil generally limits residual currents to small values. Little or no change in the status of other methods of fault-current limitation has taken place. As heretofore, the application of fault-current limitation is primarily a matter of its reaction on power-system operation, although developments have somewhat simplified this question.

4. Frequency of occurrence of ground faults has been reduced by improvements in the insulation of power lines, including improved ground-wire application and features of structural design. In the reduction of duration of ground faults, the protector tube is probably the most important development from the standpoint of low-frequency induction. Others are increased speed of circuit-breaker operation, including high-speed relaying and closely simultaneous clearances at both ends of the faulted line section, and (except for permanent faults) the Petersen coil.

These developments have had a definitely favorable reaction on low-frequency inductive co-ordination, although it is impracticable to ascertain the extent of this, taking the country as a whole.

Coupling and Shielding

5. The theory of the mutual impedances of ground-return circuits has been extended to cover circuits of arbitrary lengths and contours, and now includes also certain types of heterogeneous earth structure. Some further work is desirable in simplifying the engineering application of the theory to types of problems which may be encountered.

6. Coupling tests should be made before final decision in important cases. Development work has cheapened and simplified field testing methods and apparatus, and is continuing.

7. Methods and data for calculating reductions in longitudinally induced voltages resulting from shielding currents in usual types of shielding structures have been published. In the case of telephone cables, the voltage between conductors and sheath

(as contrasted with longitudinally induced voltage) is of interest, and in long cables, shielding by currents in the conductors as well as by those in the sheath is important. These matters are currently receiving attention.

8. Shielding by currents in conductors which become grounded through protector operation is difficult to estimate, although it has frequently been found to be of considerable importance. Additional investigations of this factor are to be carried out.

Susceptiveness

9. Possibilities of using toll cables of relatively small physical dimensions, and of new structural designs, presented by developments in the application of carrier to cables, require consideration of changes in the inherent shielding afforded by the cable structure. These and allied questions may continue to require study for some time.

10. The use of composited d-c toll-line dialing and through-supervision systems is increasing. Inclusion in these systems of arrangements for neutralizing induced voltages reduces their susceptiveness to low-frequency induction, although further study of inductive co-ordination with these and other signaling systems is needed.

11. Development work on the relay protector has been substantially completed. This device has had a good record in use as a specific measure of co-ordination.

12. Two types of neutralizing transformers have been developed. One, for neutralizing ground potentials on communication lines serving power stations, is being successfully used in practice. The other, designed for toll-line use, proved satisfactory in field trial, but the probable field of use is small.

13. A copper-oxide device for reducing acoustic disturbances has been developed for use at operators' positions. Experience indicates that it is generally satisfactory.

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Discussion

L. F. Roehmann (Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y.): The authors gave an excellent review of the progress in the art of low-frequency inductive co-ordination which has been realized in this country during the past decade. It might be appropriate to add that during that interval substantial work has been done on the other side of the Atlantic also.

In 1926 and 1930, the CCIF issued "Guiding Principles Concerning the Means for Protecting Telephone Lines Against the Adverse Effects of High-Current or High-Voltage Lines." Last year, an entirely new edition has been published ("Guiding Principles Concerning the Protection of Telecommunication Lines Against the Adverse Effects of Industrial Power Lines"). This publication, containing 150-odd pages, is an up-to-date textbook on inductive co-ordination rather than just a set of recommendations. It climaxes the co-operative efforts of the International Mixed Commission for the Study of Inductive Interference, the CCIF, and a number of other international groups and organizations. Power and communication engineers of France, England, Germany, Switzerland, Sweden, and many other countries contributed to its setting-up.

The publication is written in French but an English translation has been prepared. While many of the minor details are different in the two hemispheres, the basic conceptions are of course the same.

J. W. Milnor (The Western Union Telegraph Company, New York, N. Y.): This paper discloses a very healthy condition in the development of low-frequency inductive co-ordination. A comparison with that presented in 1931 by Messrs. Conwell and Warren makes it evident that the past ten years have produced few actual changes in the basic method of attack; instead there has been a continuous advance in the knowledge of the problem, of the mathematics which represents the variable conditions, and of the apparatus and equipment necessary to provide the desired safety and stability of service.

The scope of the discussion is so broad that within the necessary space limitations the authors have been able to describe only the most prominent advances. Fortunately there is included a bibliography which in itself is an index of the extent of the progress, and which should be of much value to the reader who desires more intimate knowledge of any phase of the problem.

The authors have dealt chiefly with the transient low-frequency interference which occurs particularly at times of fault conditions in the power system. They have perhaps underemphasized the continuous interference which may occur during normal power operation, and which often has serious effects especially to high-speed telegraph circuits, although it is rarely damaging to the telephone.

J. O'R. Coleman: Mr. Trueblood and I greatly appreciate L. J. Roehmann's remarks regarding the report of the Comite Consultatif International Telephonique. The English edition of the report of the 11th Plenary Meeting held in Copenhagen, was published in 1938 by the International Standard Electric Corporation, and contains considerable interesting information. Due to the many different conditions existing in European practice, technical, economic, and social, we do not feel that in general the work of the CCIF can be directly applied to American practice, although many of the technical findings are useful.

A Precision Rotating Standard for the Measurement of Kilowatt-Hours

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THE accuracy with which electrical energy is metered is dependent upon the apparent measured value of the kilowatt-hour used. Quite independent of the electrical operating characteristics of the watt-hour meters used or the accuracy limits within which they are adjusted, the average accuracy of a group of watt-hour meters is directly affected by the difference between the value of the kilowatt-hour used and the true value.

The apparatus used to derive the unit while satisfactory for reference does not lend itself to practical use in the checking and calibrating of watt-hour meters in commercial installations. Specially designed and compensated induction-type watt-hour meters, which are calibrated in the laboratory approximately as outlined in table I, have long been used as commercial working standards. These watt-hour meters are known as portable standard watt-hour meters and have been developed to a high degree. In fact, so well do they perform that an improvement in the method of standardizing them is justified.

It is the purpose of this paper to describe an improved system for maintaining the value of the kilowatt-hour to be used primarily for the calibrating and checking of portable standard watt-hour meters.

Analysis of Errors in Method of Checking Rotating Standards

Table I shows the limits of probable error present in the various steps of a particular system. It is evident that all of the values given in table I could add up to be (+) or could add up to be (−) if a sufficiently large number of checks were taken. The probability of either of these two conditions occurring is much less than is the probability of some steps compensating others due to differences in the sign of the errors. Should all errors add (+) the result would be

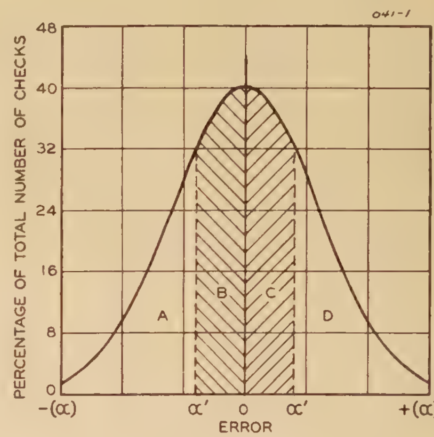


Figure 1. Absolute error in per cent

a +0.245 per cent variation, and if all (−), a −0.245 per cent error. It is important, therefore, to obtain some idea of the most likely way the error of the various steps will combine to determine what over-all accuracy is to be expected.

Paper 40-41, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 13, 1939; made available for preprinting January 3, 1940; released for final publication March 5, 1940.

J. H. Goss is engineer in charge, works laboratory, and A. Hansen, Jr., is engineer, General Electric Company, Lynn, Mass.

Consider a theoretical distribution curve, figure 1, and for the purpose of illustration let the abscissa represent a system of errors similar to table I. To avoid confusion the error limits have been designated $\pm\alpha$. If a large number of checks are made, figure 1 will represent a plot of the results. The tests showing zero error will be the most frequent, but the extreme errors will occur in a small percentage of the readings when the component errors have the same sign.

The technician must realize that with a small number of readings the average value may not be a fair one. If it should occur that in five readings a high (+) error is obtained with four smaller (+) errors, the average would be (+) and would depart appreciably from the absolute value. It is important that a sufficiently large number of readings be taken to show up the individual readings with large variations from the mean.

As the total area under the curve, figure 1, represents all of the readings, half of the area will represent half the total number of readings. The areas A, B, C, and D have been divided to make each equal to one-fourth the total area $(B+C=A+D)$. The abscissa of B is $-\alpha'$ and of C is $+\alpha'$. The combined areas $B+C$ represent half the total number of readings, and it is, therefore, reasonable to state that one-half of the readings taken are probably within the area $B+C$ and are therefore, within $\pm\alpha'$. This value of the abscissa $(\pm\alpha')$ will be referred to as the probable error.

Precision Rotating Standards Method

The schematic diagram shown in figure 2 gives the circuit and essential elements of a system of three precision rotating standards. This system is capable of maintaining a high degree of accuracy. It will first be described in its component parts and then its method of operation, together with actual performance data, will be given.

A. Rotating Standards

The rotating standards shown in figure 3 are used as the measuring elements. These were made by taking a commercial portable standard watt-hour meter, removing the register, and rewinding the current coils for a five-ampere current rating only.

The standards were removed from their cases and mounted as shown in figure 4 in a walnut case. Incandescent-lamp housings and lens systems were mounted above the meters and photoelectric cells in suitable housings were mounted below the case. Glass windows were provided in the top and bottom of the case to allow the light from the light sources to be focused through a small hole in the meter disk onto the photoelectric cell below. The case was completely sealed against dust and mounted on a vibration-free concrete wall in a (22 degrees centigrade) controlled-temperature room. Each rotating standard was carefully compensated for both unity and 0.5 power-factor lagging temperature errors (class I and class II errors).[2]

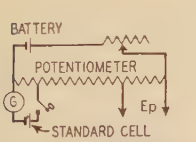
Each rotating standard, together with its light source and photoelectric cell, is considered as a unit having no functional relation with the other two. For the purpose of identification these will be called precision rotating standards numbers 1, 2, and 3.

B. Transformers

The standards were designed for 120 volts and five amperes, but a high-

Table I

Step	Fundamental Measuring Circuit and Type of Measurement	Source of Error	Limit of Error	
A—Potentiometric method of maintaining voltage and current from a standard cell using a voltage multiplier and shunt	Figure *A*—Potentiometric method of maintaining a voltage Figure *B*—Voltage multiplier method of maintaining a standardized test voltage Figure *C*—Shunt method of maintaining a standardized test current	1—Error in the standard cell	±0.01	
		2—Error in balancing cell	±0.01	
		3—Error in resistance arms	±0.01	
		4—Error in multiplier	±0.01	
		Total maximum error for sources 1, 2, 3, 4		±0.04
		5—Error in shunt	±0.01	
		Total maximum error for sources 1, 2, 3, 5		±0.04
		Total maximum error		±0.80
B—Calibration of dynamometer wattmeter on direct current	Figure *D*—Potentiometric method of calibrating a dynamometer wattmeter on direct current	1—Holding deflection of wattmeter at scale point	±0.02	
		2—Holding voltage	±0.01	
		3—Error in voltage value step *A*	±0.04	
		4—Error in current value step *A*	±0.04	
		Total maximum error		±0.11
C—Calibration of induction-type watt-hour meter	Figure *E*—D-c to a-c dynamometer wattmeter transfer	1—Holding wattmeter setting (load varying)	±0.04	
		2—Error in checking wattmeter step *B*	±0.11	
		3—Change in wattmeter calibration from check value	±0.03	
	Figure *F*—Time element of power equation $W = \frac{Kh \times N \times 3{,}600}{t}$ W = meter watts Kh = meter disk constant N = revolutions t = time (seconds)	4—Punching key (human error)	±0.05	
		5—Error in measuring chronograph sheet	±0.01	
		6—Error in timing mechanism	±0.005	
		Total maximum error		±0.245



TWO OF FIGURE A REQUIRED, ONE FOR VOLTAGE MULTIPLIER SOURCE (Ep_1) AND ONE FOR CURRENT SHUNT BALANCING VOLTAGE (Ep_2)

FIGURE A

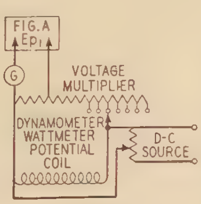


FIGURE B

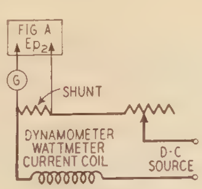


FIGURE C

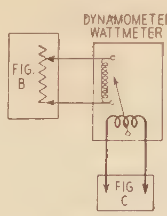


FIGURE D

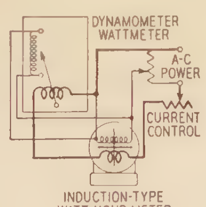


FIGURE E

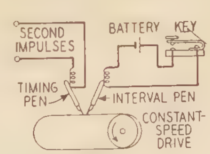
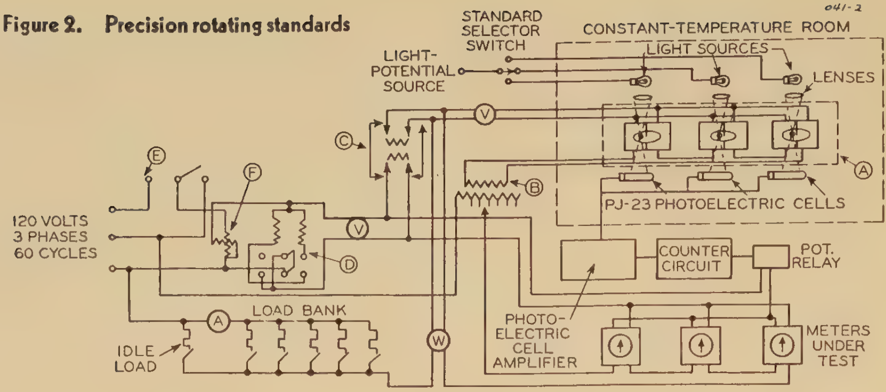


FIGURE F

Figure 2. Precision rotating standards



A—Three special *IB* standards mounted in dust-tight case, special 0.060-inch hole in disks for light shutter

B—Current transformers, ratios 1:0.2, 0.25, 1, 2, 2.5, 10; tap chosen by jumper

C—Potential transformer, 2:1, connected by jumpers

D—Potential transformer, 1:2, connected by 100-ampere switch (for low contact resistance)

E—100-ampere switch for phase selection

F—Voltage regulator

accuracy current transformer having a Mumetal core is used to allow the standards to operate at five amperes under all test conditions. The ratios available are shown under *B* in figure 2 and allow for all points required for the commercial checking of portable rotating standards. The current transformer has a ratio error within 0.04 per cent on all coils and a phase angle error within one minute on all coils.

A potential transformer is provided for 240-volt operation.

Not only are the transformers designed for low inherent errors, but they are considered as an integral part of the precision rotating standard circuits and all calibrations made in accordance with table I are made on the combination. This method of calibration was employed using instruments for all current ratings to check the meter and transformer combination. Although the ratio and phase-angle errors were determined for the transformers, they were not used in arriving at the calibration of the standards.

C. Photoelectric-Cell Testing Relay Circuit and Auxiliary Switching

A photoelectric-cell amplifier, figure 2, is provided which operates a counter circuit which can be preset to energize through the potential relay the potential circuit of one or more portable standard watt-hour meters and to keep the potential circuit or circuits energized for the preset number of revolutions of the precision rotating standard.

By means of a suitable switch, precision rotating standard number 1, number 2, or number 3 may be used to control the portable standard watt-hour meters under test. The repeatability of the relays and photoelectric circuit is in the order of ±0.01 per cent for ten revolutions. The precision rotating standard being used runs at the selected load continuously and only the standard under test is started and stopped.

Method of Use and Results

Each of the three precision rotating standards is operated continuously when not being used for test work at two per cent of rated current and with rated potential applied. This eliminates any error due to potential-coil heating.

The error in the calibration of each of the precision rotating standards is determined by repeated checks in accordance with the steps shown in table I. At no time since the beginning has any change been made in the adjustments of any of the three standards. It is then desirable to cross-check the precision rotating standards in terms of one another using a portable standard watt-hour meter as the transfer medium. If the standard used for the transfer has a known history of calibration, it is valuable as a reference to show up any major changes in absolute values of any of the precision rotating standards.

It would be desirable not to introduce the fourth standard for the purpose of intercomparison. It is possible to use one of the three precision rotating standards for this purpose, and this will eventually be done. The results of using a transfer have been quite satisfactory to date.

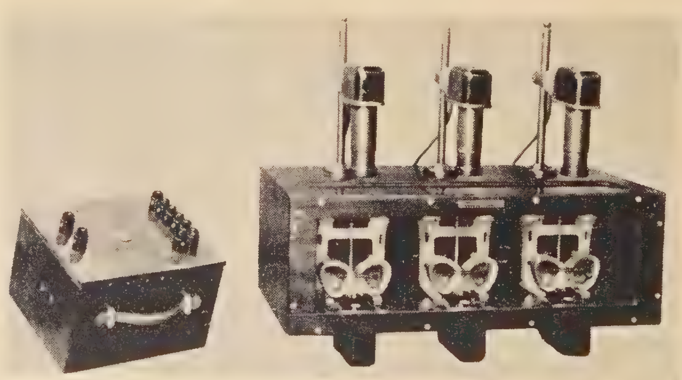
Figure 5 shows the results of such an intercomparison over a period of five months for the five-ampere 120-volt load point operating at unity power factor. Precision rotating standard number 1 is assumed to be correct and number 2 and number 3 are plotted in terms of their deviation from number 1.

The maximum variation in number 2 from the original reading is +0.06 per cent and of number 3, −0.06 per cent over the five months' period. Note that at the end of the period number 2 is +0.03 per cent above the original reading and number 3 is −0.01 per cent below its original reading.

Figure 6 shows the same intercomparison as figure 5 except that the load point used was 120 volts, five amperes, and power factor 0.5 lagging. It is to be expected that a greater variation will be obtained using this load due to other variables operating. For example, variation in phase angle, wave form, frequency, and temperature are more effective in

Figure 3. Precision rotating standards without case

Figure 4. Precision rotating standards complete with light sources, photoelectric tubes, and precision current transformer adjacent



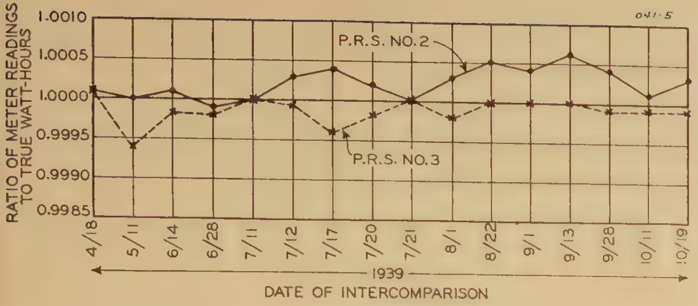


Figure 5. Intercomparison data on precision rotating standards corrected in terms of standard number 1

Five amperes, 120 volts, 60 cycles, unity power factor

producing calibration change than at unity power factor. The maximum variation of precision rotating standard number 2 is +0.09 per cent and of precision rotating standard number 3, −0.12 per cent. At the end of the period, number 2 is +0.06 per cent above the original reading and number 3 is +0.02 per cent above the original reading. No change in the adjustments were made at any time after the initial readings were taken.

Figure 7 shows the results of 36 separate checks made over the five months' period in accordance with table I. The most probable error in absolute calibration is ±0.04 per cent from the mean. The initial instrument check was assumed to be correct for the purpose of plotting the data in figure 7. It is evident that the initial point was low by −0.06 per cent and a better value of the absolute calibration is the peak ordinate or +0.06 per cent above the initial reading. The distribution curve was drawn by first determining the mean and standard deviation for the results of the 36 checks and calculating the ideal curve to fit the data.

Certainly, these standards are running together within far closer limits than any single instrument check can be relied upon to reveal. This is, however, the ideal condition for obtaining the true mean value in accordance with table I. If the precision rotating standards remain constant and the interchecks reveal that they are, then their calibration will approach the value of the maximum ordinate in figure 7. As all these standards were intercompared, figure 7 represents the instrument check on each of the standards.

Should some factor influence all of the standards to drift at exactly the same rate, the intercheck would not reveal the drift. As continual periodic instrument checks are obtained, curves similar to figure 7 can be plotted and compared one with another to show up this drift.

The actual use of this method for checking portable standard watt-hour meters is evident. Each precision rotating standard has a definitely established calibration so that one revolution of the disk under a given load corresponds to a definite kilowatt-hour value. By placing the portable standard watt-hour meters to be checked as shown in figure 2, any one of the three precision rotating standards may be selected to deliver a given number of kilowatt-hours to them. The ratio of the reading of the individual portable standard to the known value of the precision rotating standard is a measure of its accuracy.

The average of the calibration obtained using each of the three precision standards in turn to control the portable standard watt-hour meter or meters under test will give the highest precision. In

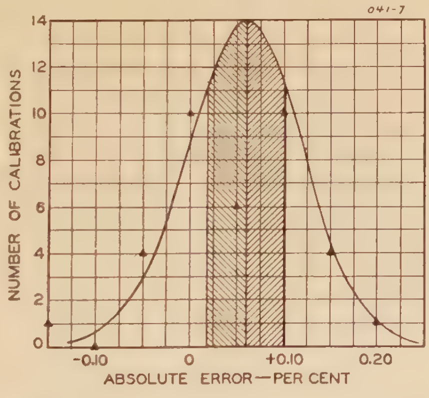


Figure 7. Curve of distribution of absolute error for repeated checks of precision rotating standards

Five amperes, 120 volts, 60 cycles, unity power factor

practice, however, the additional accuracy is not justified because of the additional time required.

The high accuracy of the photoelectric testing system makes it necessary to take runs of no longer than 60 seconds for any given point. This greatly speeds

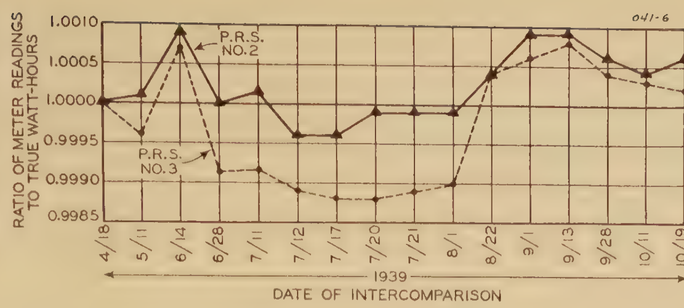


Figure 6. Intercomparison data on precision rotating standards corrected in terms of standard number 1

Five amperes, 120 volts, 60 cycles, 0.5 power factor lagging

up the calibration check of the portable standard watt-hour meters.

Conclusions

1. It has been demonstrated that for the highest accuracy of calibration of portable standard watt-hour meters using instruments, a number of readings must be taken and properly weighted.

2. A new system of precision rotating standards has been described that has high inherent accuracy together with fast operation.

3. With care it is entirely practical by the system described to insure the absolute accuracy of the kilowatt-hour used in checking standards to within 0.06 per cent at unity power factor loads and 0.12 per cent at 0.5-power-factor lagging loads.

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Discussion

George B. Schleicher (Philadelphia Electric Company, Philadelphia, Pa.): The authors are to be congratulated upon their contribution to the important field of maintaining the accuracy of laboratory-standard watt-hour meters. The elimination of "start-and-stop" errors in the so-called master standard, by causing it to rotate continuously during the calibration, serves also to eliminate such errors from the working standards when their corrections are determined by tests *over the same intervals that are used in service.*

From a practical standpoint the limits of accuracy as covered in table I appear rather small. For example, holding a wattmeter setting within 4/100 per cent with varying load (table I, step *C*-1) would be a very difficult problem in the average utility laboratory where the source of energy supply is from a distribution system. In the calibration of standard watt-hour meters with wattmeters, manual control to maintain a constant load introduces a human element of error, and there is a need for an *automatic* means of obtaining *constant wattage* independent of voltage variation. We have succeeded in accomplishing this, at least experimentally, by electronic means.

In the standard described by the authors, bearing friction is reduced by operating the standard only at full-load speeds, but possibly further improvements can be made in this direction. While the magnetic suspension is not new, modern magnetic materials, as for example Alnico, have made possible the design and construction of practical meter bearings of this type. This construction may prove highly desirable for

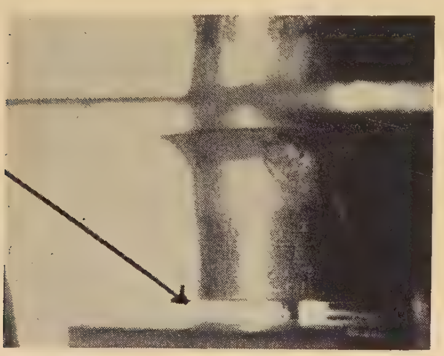

Figure 1. Enlarged view of magnetic suspension on watt-hour meter

The arrow points to the air gap which represents the bearing surfaces

service meters. Figure 1 of this discussion shows such a bearing developed by Walter C. Wagner of the Philadelphia Electric Company, and constructed of magnet materials contributed at our request by the General Electric Company. In the figure the air gap indicated by the arrow shows a greatly enlarged view of the bearing. Meter-performance tests over extended periods show consistent results superior to those of pivot and jewel bearing construction particularly at light load, thus permitting accurate performance to be maintained in standards and meters at lower operating speeds than with the conventional types of bearings. This type of suspension would undoubtedly further improve the uniformity of performance of the precision standards described by the authors.

W. J. Seeley (Duke University, Durham, N. C.): I should like to ask a question which is old but the philosophy of which is quite intriguing. It may have been answered to the satisfaction of manufacturers long ago, but not enough information has been given in print to put at rest a question which comes up with fair regularity. It is conceivable that by proper construction and adjustment the greater part of the weight of the rotor on the lower jewel may be removed by magnetic attraction, thus considerably reducing the friction loss. The question then is this: In an effort to reduce the rotation losses of your precision rotating standard, had you considered the possibility of reducing the weight of the rotor on the jewel by the use of a permanent magnet suspended just above the upper end of the shaft?

Wm. M. Young (Ohio University, Athens): Of particular interest in this paper is table I giving assigned values to the various sources of error encountered in standardizing and calibrating rotating standard watt-hour meters. It is assumed that all measurements were made using sinusoidal waves of current and voltage and that the authors were not concerned with irregular wave forms.

The question naturally arises as to whether or not the errors in the instrument check are inherent and whether they cannot be minimized by any standardizing laboratory if the equipment is properly aged and maintained at a constant temperature and if repeated trials are made and the results plotted on a probability curve. Naturally any laboratory can, in this way, reduce the 0.11 per cent accumulated error in the wattmeter's calibration by using proper care.

Might I ask the authors about the 0.03 per cent error assigned in *C*-3 "change in wattmeter from check value". Are there any data available on the accuracy of the determination of this error? Naturally it can be partially reduced if the time interval between checking the meter and using the meter for a watt-hour meter calibration is reduced to a minimum.

It would seem that the greatest contribution of this paper lies in the substitution of

1. A machine-switching machine for a hand-switching machine. This naturally affects the magnitude of errors *C*-4, *C*-5, and *C*-6. They total, as indicated by the table, 0.065 per cent.
2. Multiple standards cross-checked against each other in place of human observation for *C*-1.

In figure 5 might I ask about the drift of the readings in rotating standards with time? It would seem that an aging effect might be here showing up and that the meters would eventually tend to stabilize at some constant error.

In figure 7 might I ask why the point at 0.05 per cent error was not used in the determination of the probability curve? It would seem that more data should be taken before a good probability curve can be drawn and that results should not rely on merely 36 readings.

A. E. Vivell (Princeton University, Princeton, N. J.): It is gratifying to see that the actual title of this paper describes the meter as a "precision" meter and not as a "primary" standard as announced in the advance notices. It would be unfortunate to handicap such an excellent and interesting development with a misnomer.

The calibration procedure described is most thorough and provides a very comforting check on the constancy of these meters. However, the figures in table I seem to show a probable error of about 0.08 per cent in the watt-hour used in checking the rotating standard. It would seem, therefore, that the probable variation of 0.04 per cent from the mean shown in figure 7 is somewhat low. An exceedingly slight change in only four of the calibration points (at 0 and +0.10 per cent) could make the curve much flatter. If the point at +0.05 per cent were taken into account the probable error would be increased to about 0.08 per cent and the theory of probability restored to favor.

This paper again brings home the fact that the measurement of a watt-hour is handicapped by the lack of a simple scheme of measurement. When the meter error becomes less than the error of the standard it is time to work for better standards. It would be interesting to know if the authors have considered trying to improve their watt-hour by means of some other scheme of calibration; for example, a calorimeter or some other energy device.

A. Hansen, Jr.: An analysis of the discussions of our paper reveals four general points of comment: first, the limits of errors shown in table I; second, the manner in which our data were handled and the derivation of the probability curve shown in figure 7; third, bearing considerations; and fourth, the apparent better accuracy of the watt-hour meter than the calibrating standards.

The values shown in table I represent the results obtainable with extremely careful control of each step starting with the standard voltaic cell. Special sources of power of as constant regulation as possible are used without the use of electronic regulators. The authors feel that the values shown are representative for the method, and are the result of a number of years of experience.

An automatic device for holding load might be applied to some advantage in the system described. Up to the present time, however, the authors have had no experience with such a device.

The authors recognize the fact that insufficient data were obtained to fix positively error magnitudes. It was the purpose of the paper to describe a method and a system of arriving at a precise value of the watt-hour.

The probability curve in figure 7 was plotted considering all calibration values and is not sketched in from the grouped data plotted but was calculated from the actual data.

Inasmuch as the precision rotating standards rotate continuously at full-load speed for all check points, the variations due to bearing friction are practically negligible. A magnetic-suspension type bearing is an interesting device in view of the new magnetic materials available.

At the present time no practical way of obtaining the value of the watt-hour is known to the authors that is basically different from the method outlined in table I. Energy-equivalent methods have been experimented with such as the calorimeter. The difficulty in using the calorimeter is not with measuring the heat values, but in determining the correction for heat loss.

In conclusion, the authors wish to express their appreciation for the very excellent criticisms they have received and hope that all questions have been satisfactorily answered.

Transactions

Preprint of Technical Papers Comprising Pages 417–88 of the 1940 Volume

Lightning Currents in Arresters at Stations

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A CO-OPERATIVE field investigation of the lightning currents discharged by arresters at stations was undertaken in 1936, by the engineering departments of the American Gas and Electric Service Corporation and the General Electric Company. Data have previously been published on the currents discharged by distribution lightning arresters[1,2,3] but little information is available on the duty required of arresters located in stations, where considerable influence on incoming lightning waves may be produced by a large number of circuits connected to one bus, by the capacitance to grounded steel work in the station, by the more or less sheltered location of some stations, and by types of construction commonly used for transmission lines.

The data so far obtained show that there are large variations in the number of arrester discharges from season to season, and that due to local conditions the duty on arresters is far more severe in some locations than others, making it difficult to arrive at a representative average. Hence the investigation is to be continued in order that the effects of these factors may be better determined. Some redistribution of field installations may be made to provide more information on points where the data have been meager.

Scope and Conduct of Investigation

In this investigation the field work was carried on for four years (1936–1939) on four American Gas and Electric Company properties; the Ohio Power Company in Ohio, the Appalachian Electric Power Company in Virginia, the Atlantic City Electric Company in New Jersey, and the Indiana and Michigan Electric Company in Indiana. This diversified territory provided an opportunity for studying lightning conditions as affecting arresters, on properties employing different practices, and with isokeraunic levels varying from 27 to 45 thunderstorm days per year.

Measurements of arrester discharge currents were made with surge-crest-ammeter links[4] mounted on each leg of each three-pole arrester, in a straight part of the conductor between the arrester and the line. Typical field installations are shown in figures 1, 2, and 3. Links were serviced approximately every two weeks during the lightning season for four years, and any which indicated that current had passed through the arrester were removed for calibration and replaced with demagnetized links. The magnetized links were checked in the field in some cases, but received a final calibration at the Pittsfield works of the General Electric Company.

The current measuring installations are listed in table I, where they are grouped

Figure 1. Wooden bracket supporting two surge-crest-ammeter links on lead to lightning arrester

Figure 2. Surge-crest-ammeter link installations on all three poles of 33-kv oxide-film lightning arrester

Figure 3. Field servicing of surge-crest-ammeter links on Thyrite lightning arrester on 132-kv energized circuit

Paper 40-59, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 24, 1939; made available for preprinting January 3, 1940; released for final publication February 28, 1940.

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A large number of people in several organizations have contributed to make an investigation of this type possible and to correlate the data in suitable form for presentation. The authors wish to express their appreciation to the Ohio Power Company, the Appalachian Electric Power Company, the Atlantic City Electric Company, and the Indiana and Michigan Electric Company, where the field work was done; and to those in the Engineering Departments of the General Electric Company and the American Gas and Electric Service Corporation who supervised the work and analyzed the records. Acknowledgment is made to the helpful assistance of George D. Lippert of the American Gas and Electric Service Corporation for correlating the records on which the paper is based, and to Doctor K. B. McEachron and D. D. MacCarthy of the General Electric Company for their assistance in organizing and directing the progress of the investigation.

1. For all numbered references, see list at end of paper.

according to several different classifications. The installations were confined to arresters in stations only, and included arresters connected to lines where they entered the stations, arresters on or immediately adjacent to power transformers, and arresters connected to station busses. The arresters were of several different designs. Approximately 75 per cent were designated by the manufacturer as "station type" and 25 per cent as "line type". All circuits involved operated with grounded neutrals, at line-to-line voltage ratings of 11 to 132 kv.

One hundred three-pole arresters were equipped in 1936 for the measurement of lightning discharge currents. This number was increased each year until 1939, when 166 were under investigation. The total three-pole arrester-years for the four-year period was 580*, making an average of 145 under study each year. On the basis of single-pole arresters, the study included 1,734 arrester-years, or an average of 433.5 each year.

Number of Records Obtained

A total of 459 records of lightning currents discharged by single-pole arresters were obtained during the four-year period, or 0.79 records per three-pole arrester per year. The maximum number of single-pole records obtained during the four-year period on any one three-pole arrester was 29, and three other arresters yielded 24 records each.

Table I. Number of Three-Pole Lightning Arresters Equipped With Surge-Crest-Ammeter Links, 1936 to 1939 Inclusive

Type of Arresters or Connected Transmission Lines	Number of Three-Pole Arresters Equipped With Surge-Crest-Ammeter Links				
	1936	1937	1938	1939	Total
Arrester *A*	5	0	0	0	5
Arrester *B*	2	5	5	5	17
Arrester *C*	62	105	105	105	377
Arrester *D*	26	30	29	27	112
Arrester *E*	5	12	23*	29**	69**
Total	100	152	162*	166**	580**
Station-type arresters	74	122	122	122	440
Line-type arresters	26	30	40*	44**	140**
Total	100	152	162*	166**	580**
Arresters connected to:					
11-kv lines	0	2	2	2	6
22-kv lines	17	30	33	32	112
27-kv lines	0	23	25*	31**	79**
33-kv lines	46	46	48	47	187
44-kv lines	1	1	1	1	4
66-kv lines	1	11	13	13	38
88-kv lines	1	1	1	1	4
132-kv lines	34	38	39	39	150
Total	100	152	162*	166**	580**
Arresters connected to:					
Wood-pole lines					
No ground wire	14	30	32	31	107
One ground wire	30	46	53*	58**	187**
Steel-tower lines					
No ground wire	5	9	9	9	32
One ground wire	38	43	44	44	169
Two ground wires	2	7	7	7	23
Mixed circuits	11	17	17	17	62
Total	100	152	162*	166**	580**

* Includes one two-pole arrester installation. ** Includes five two-pole arrester installations.

Table II summarizes the number of records per arrester for the 85 three-pole arresters that remained in service during the entire four-year period. These were all on Ohio Power Company and Appalachian Electric Power Company circuits, where the severity was above the average for the four operating companies.

Table II. Number of Records Per Arrester During Four-Year Period, 1936–39

Based on 344 Records From 85 Three-Pole Arresters Which Remained in Service During the Entire Four-Year Period, all on Ohio Power Company and Appalachian Electric Power Company Circuits

Number of Single-Pole Records Per Arrester	Number of Arresters	Per Cent of Total Arresters
0	27	31.7
1	17	20.0
2	9	10.6
3	1	1.2
4	7	8.2
5	7	8.2
7	3	3.5
8	2	2.4
9	1	1.2
10	1	1.2
11	1	1.2
12	2	2.4
14	1	1.2
17	1	1.2
20	1	1.2
24	3	3.5
29	1	1.2
Total	85	100

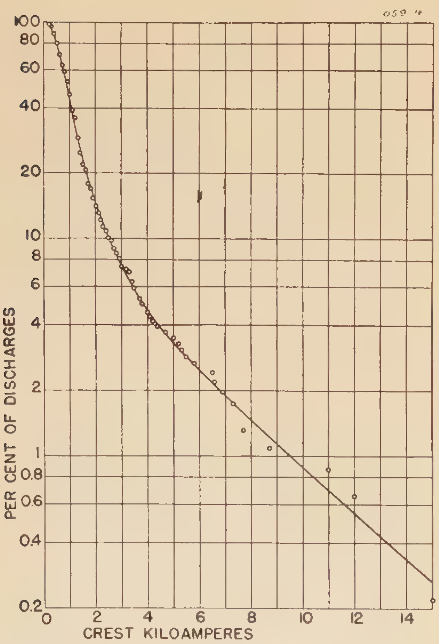


Figure 4. Current magnitude of recorded arrester discharges

Curve shows per cent of discharges with current magnitude at least as great as indicated

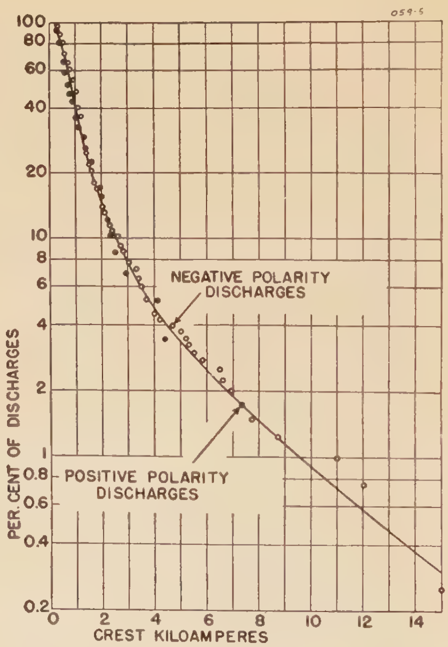


Figure 5. Comparison between magnitudes of positive and negative polarity discharges

Curve shows per cent of discharges with current magnitude at least as great as indicated

* Including six installation-years on two-pole arresters.

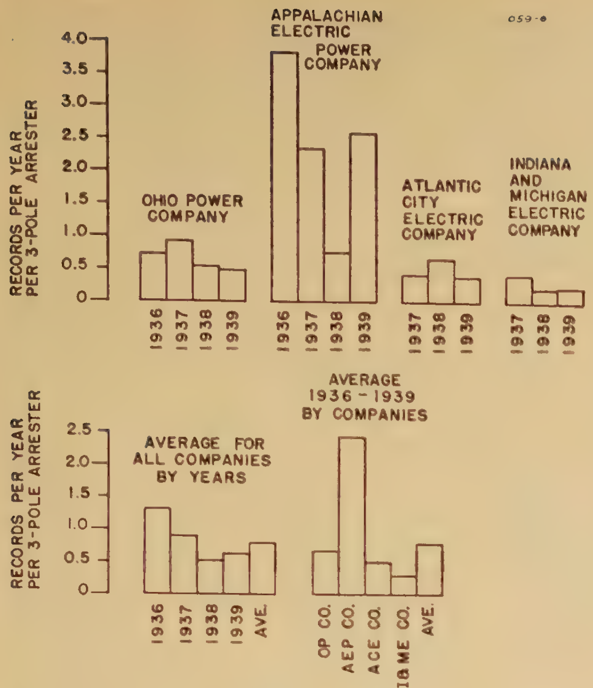


Figure 6 (left). Variation in number of records obtained from year to year, and between different localities

Figure 7 (right). Effect of line construction on number and magnitude of arrester discharge currents

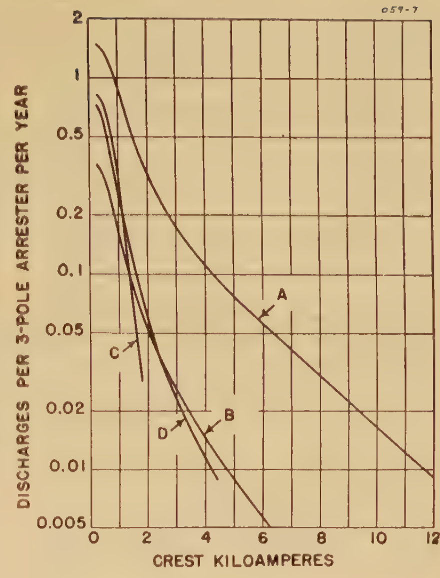
Curves show number of discharges per three-pole arrester per year which have current magnitudes at least as great as indicated

A—Wood-pole lines without ground wires

B—Wood-pole lines with ground wires

C—Steel-tower lines without ground wires

D—Steel-tower lines with ground wires



Magnitude of Currents

The highest individual arrester discharge current recorded was 15,000 amperes, and 16 measurements or 3.5 per cent of the total were 5,000 amperes or more. Arresters at certain locations were subjected repeatedly to high discharge currents.

In many cases there were several arresters in one station connected so that they could operate in parallel. The current which any one might have been called upon to discharge, in the absence of the others, may be estimated by adding together the currents recorded simultaneously in all of the arresters. The highest value obtained in this way for any one phase is 19,000 amperes.

The current measurements obtained are summarized in table III, where the maximum, minimum, and the median current (the current exceeded in 50 per cent of the cases) are listed for several operating conditions, together with the number of current measurements and arrester installation-years upon which the values are based. Figure 4 shows how the 459 current records were distributed with regard to magnitude.

Table III. Summary of Recorded Arrester Discharge Currents, 1936 to 1939 Inclusive

Type of Arresters or Connected Circuits	Number of Three-Pole Arrester-Years	Number of Single-Pole Discharges Recorded	Values of Discharge Currents in Amperes Max.	Min.	Median
Arresters connected to:					
11-kv lines	6	2	500	350	425
22-kv lines	112	97	12,000	350	1,200
27-kv lines	79	29	3,800	Trace	950
33-kv lines	187	169	15,000	Trace	850
44-kv lines	4	4	8,700	1,400	4,200
66-kv lines	38	11	7,700	1,000	1,300
88-kv lines	4	11	1,100	Trace	550
132-kv lines	150	136	4,100	Trace	700
Total	580	459	15,000	Trace	950
Arresters at stations with only one arrester and					
1 line	28	34	8,700	Trace	900
2 lines	111	158	15,000	Trace	1,050
3 lines	29	59	5,800	Trace	1,100
4 lines	20	7	2,200	200	450
5 lines	3	0			
6 lines	4	2	800	600	700
Arresters connected to:					
Wood-pole lines					
No ground wires	107	166	12,000	Trace	1,100
With ground wires	187	72	5,200	Trace	900
Steel-tower lines					
No ground wires	32	26	1,800	Trace	850
With ground wires	192	151	11,000	Trace	650
Mixed circuits	62	144	15,000	250	1,000
Total	580	459	15,000	Trace	950

Polarity of Currents

The polarity of 401 records, or 87.6 per cent of the total, was negative, and of 58, or 12.4 per cent, was positive. This proportion is intermediate between the previously reported values of 63 per cent negative for distribution arrester discharge currents,[1] and 95 per cent negative for lightning currents measured in steel tower legs of transmission lines.[5] In this investigation, the data do not show any recognizable effect of line construction, locality, or circuit voltage rating on the proportional numbers of negative and positive polarity records. Figure 5 shows that the distribution of the negative-polarity records with regard to current magnitude was substantially the same as for positive-polarity records.

Variability Between Localities and Seasons

The data shown in figure 6 indicate that the number of arrester discharges varies considerably from season to season, and is consistently greater in some localities than in others. Seasons which are severe in some localities are comparatively mild in others. The greatest number of discharges per arrester per year was 3.84 for the Appalachian Electric Power Company in 1936, and the smallest number was 0.22 for the Indiana and Michigan Electric Company in 1938. The ratio between these two extremes is 17.5 to 1. During the entire period of the investigation, the average number for the former company was over 8 times that for the latter, although the average isoke-

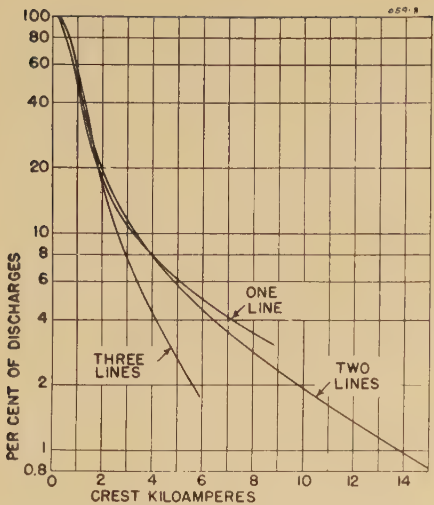


Figure 8. Effect of number of connected lines on magnitude of currents discharged by arresters

Curves show per cent of discharges with current magnitude at least as great as indicated, and include data only from stations with one arrester each

Table IV. Multiphase Arrester Operations

Type of Line Construction	Number of Cases Involving: One Phase Only	Two Phases	Three Phases
Steel towers, with ground wire	55	21	18
Steel towers, no ground wire	13	2	3
Wood poles, with ground wire	38	11	4
Wood poles, no ground wire	30	26	28
Mixed line construction	11	6	7
Total	147	66	60
	Per Cent of Cases Involving: One Phase Only	**Two Phases**	**Three Phases**
Wood poles, no ground wires	35.7	31.0	33.3
Other three types of construction	64.2	20.6	15.2

raunic level for the former location was less than twice that for the latter. Among the several factors which may have contributed to this difference are the flashover values of the lines involved, height of conductors above ground, presence of ground wires, and the frequency with which installations were inspected for magnetized links. However, when all known variables are taken into account, it is evident that the number and magnitude of discharge currents is strongly influenced by local conditions which can be evaluated only by experience over a period of several years. Therefore, it must be recognized that conditions may be encountered in service which are quite different from those reported here.

Effect of Circuit Voltage

The data were examined to determine the effect of variation in the rated operating voltage on the severity of arrester discharge currents, but any consistent trend which may exist was obscured by other influences such as the effects of line construction and local conditions. It may be possible to evaluate this effect when more data are available.

Effect of Line Construction

Figure 7 and table III show that arresters connected to wood-pole lines without ground wires are subjected to considerably more severe duty than are arresters on other types of circuits, particularly with regard to the number of high currents which they must discharge. They must pass currents of 5,000 amperes or more about ten times as often as other arresters. Less difference exists between the other types of construction included in figure 7.

Effect of Multiple Circuits

In figure 8 are shown the results obtained at stations operating with only one lightning arrester each. The curves, shown for cases where one, two, or three transmission lines enter the station, indicate that there is some reduction in the magnitude of currents which the arrester must discharge, as the number of lines is increased. Five per cent of the recorded arrester currents exceeded 6,000 amperes where there was one line, 5,600 amperes where there were two lines, and 3,700 amperes where there were three lines.

It is significant that of the 85 three-pole arresters included in table II, including many at stations with several arresters, over 50 per cent were at stations with four or more incoming lines; yet all of the 11 arresters which produced ten or more records each were at stations with three lines or less.

Multiphase Operations

Data from all arresters involved in the investigation are summarized in table IV to show how many times records of discharge current were found on only one phase of a three-pole arrester, on two phases simultaneously, and on all three phases simultaneously. This table indicates that for wood-pole lines without ground wires, more than one phase was involved in about two-thirds of the cases, and for other types of construction, more than one phase was involved in only about one-third of the cases. For each type of construction the number of two-phase operations was approximately equal to the number of three-phase operations.

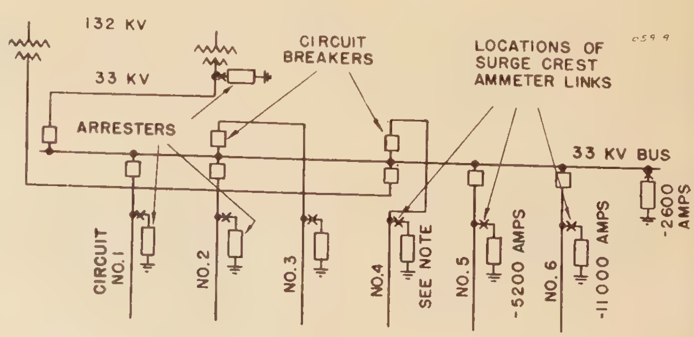
Discharge of Arresters Connected in Parallel

In some of the stations there was an arrester connected to each line where it entered the station, and additional arresters connected to the station bus or power transformers or both. The total number of three-pole arresters in any one station, so connected that they could operate directly in parallel, varied from one to ten. Data are presented in table V showing the number of times records of discharge currents were found simultaneously on several such arresters in one station, indicating that they probably discharged in parallel.

The maximum number of arresters apparently discharging in parallel, was five, in a case where there were but five arresters in the station. Three arresters

Figure 9. One-line diagram of 33-kv connections at Newcomerstown substation, Ohio Power Company

Current of −450 amperes recorded on phase 2 of this arrester. All other records on phase 1



 Gross, McMorris—Lightning Currents

discharged in parallel on three different occasions, with 4, 8, and 10 arresters respectively in the station, so connected that parallel operation was possible. Two arresters discharged in parallel on 24 different occasions, involving the same two arresters in 10 cases.

A case at a 33-kv substation is of particular interest. The circuit arrangement was as shown in figure 9. Circuits number 2 and number 5 in this sketch were on wood poles and the remaining circuits were on steel towers. All had overhead ground wires. A current of 11,000 amperes was discharged by one pole of the arrester on circuit number 6. Simultaneously a discharge of 5,200 amperes was recorded through the same phase of the arrester on circuit number 5, and one of 2,600 amperes was recorded through the same phase of the bus arrester. No discharges were recorded on the other phases of these arresters, and the only record obtained on the arresters on the other lines which were two, three, four, and five bays distant from the arrester which carried the heaviest current, was 450 amperes on another phase of the arrester connected to circuit number 4.

The curves of figure 10 show that the individual arrester currents discharged when two or more arresters discharge in parallel are in general higher than when only one of the parallel arresters discharges.

Equipment Failures

The only failure of lightning arresters included in the four-year investigation, involved one old-type arrester operating under compromise conditions on a 132-kv circuit, with the possibility of voltage being applied in excess of the manufacturer's rating. This application was made in an attempt to protect power transformers which were of an old design, with an impulse strength considerably below present-day standards. It therefore appears that the arresters involved in the investigation have a discharge capacity adequate for discharges of the magnitude and duration which they experienced.

Five cases of bushing failure occurred. The bushings concerned were of an old type, some ten or more years old, and due to the fact that all cases were internal bushing failures, it is believed they are chargeable to deterioration rather than lack of adequate protection. In one case the current through the arrester was 12,000 amperes; in another case, 2,400 amperes; and in three cases, no currents were indicated. It is interesting to note that in all five cases, the bushings which failed were of the order of 30 to 70 circuit feet from the nearest lightning arrester. Four of the bushings were rated and operating at 33 kv and one at 22 kv.

One bus-support flashover occurred on a 33-kv bus. This was of an old design, the electrical characteristics of which are unknown.

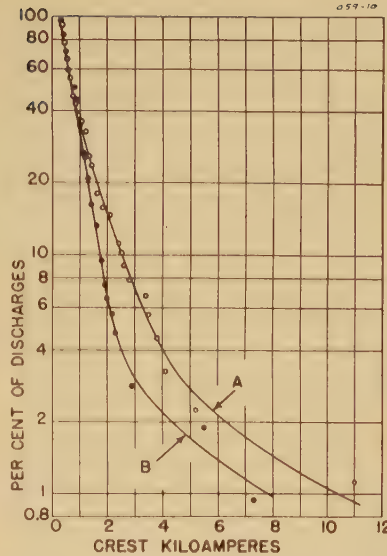


Figure 10. Comparison of (A) discharge currents in cases where two or more arresters discharged in parallel, with (B) cases where only one of several parallel arresters discharged

Curves show per cent of discharges with current magnitude at least as great as indicated

Table V. Operation of Arresters Connected in Parallel

Number of Three-Pole Arresters in Station	Number of Three-Pole Arrester-Years	Number of Cases in Four Years When Records of Discharge Were Found Simultaneously on: One Arrester	Two Arresters	Three Arresters	Four Arresters	Five Arresters	Over Five Arresters
1	195	142					
2	105	27	13				
3	7	3	0	0			
4	67	7	5	1	0		
5	62	11	2	0	0	1	
6	30*	4	2	0	0	0	0
7	9	0	0	0	0	0	0
8	60	9	1	1	0	0	0
9	0	0	0	0	0	0	0
10	30	6	1	1	0	0	0
Totals	565*	209	24	3	0	1	0

* Includes five two-pole arresters.

Table VI. Protection Given by Arresters

Assuming Two Circuits Connected to Bus, With Traveling Wave Entering on One

Circuit Voltage Rating, Kv	Three-Pole Arrester-Years	Maximum Safe Impulse, Kv	Corresponding Discharge Current, Amperes	Number of Discharges Recorded: Total	Number of Discharges Recorded: Unsafe Without Arrester	Number of Single-Pole Discharges Per Three-Pole Arrester Per Year: Total	Number of Single-Pole Discharges Per Three-Pole Arrester Per Year: Unsafe Without Arrester
11	6	104	296	2	2	0.33	0.33
22	112	144	340	97	97	0.87	0.87
27–33	266	180	368	198	176	0.74	0.66
44	4	232	460	4	4	1.00	1.00
66	38	324	596	11	11	0.29	0.29
88	4	412	720	11	4	2.75	1.00
132	150	600	1,000	136	47	0.91	0.31
11–33	384			297	275	0.77	0.72
44–88	46			26	19	0.57	0.41
132	150			136	47	0.91	0.31
All	580			459	341	0.79	0.59

Protection Given by Arresters

The amount of benefit obtained from the arresters becomes apparent when calculations are made to show how many of the recorded disturbances would have resulted in voltages considered unsafe in the absence of arresters. In table VI, the values assumed for maximum safe impulse voltage are 80 per cent of the proposed AIEE and ASA standard chopped-wave impulse test voltages for new transformers. The corresponding arrester discharge current is calculated on a traveling wave basis, assuming one incoming and one outgoing transmission line, with an arrester at the station. All discharges recorded on lines of the rating in question, with currents above the calculated value, are then considered to have

resulted from traveling waves which would have produced unsafe voltages in the absence of arresters. A mathematical analysis on this basis is not valid for the higher-current discharges resulting from direct strokes near the stations, in which case successive reflections of traveling waves must be taken into account. Such waves would, however, almost surely be unsafe, and since the current magnitudes would likely be much higher than the values shown in table VI, the mathematical analysis would indicate them to be unsafe.

The table shows that a considerable number of the recorded surges in the 132-kv class, and nearly all of the recorded surges in lower-voltage classes would have been unsafe in the absence of arresters. The number of unsafe waves per three-pole arrester per year decreases progressively as system voltage is increased, ranging from 0.72 for 11–33 kv to 0.31 for 132 kv.

Note that the calculated values in table VI are based on the assumption that a traveling wave entered the station on one conductor only, and that there was a second three-phase line connected to the station bus to provide a path for an outgoing traveling wave. These assumptions were made to simplify the calculations, and appear to represent a fair approximation of the average conditions. For 7.4 per cent of the recorded discharges, dead-end circuits were involved, which would increase the severity as compared to that for the assumed conditions. For 75 per cent of the discharges, lightning currents entered the station over two or more conductors, which would also increase the severity. For 40 per cent of the discharges, there were more than two lines connected to the bus, which would reduce the severity.

Conclusions

1. The data obtained indicate that the number and magnitude of discharge currents through arresters in stations is strongly influenced by local conditions and seasonal variations, and representative values can be determined only by experience over a period of several years. Therefore, conditions may be encountered in service which are quite different from those reported here.

2. A total of 459 single-pole arrester discharge currents were recorded in a four-year investigation, on an average number of 145 three-pole arresters located in stations. This is a rate of 0.79 single-pole discharges per three-pole arrester per year, which may be compared to the previously published rate of 0.51 discharges per single-pole arrester per year on rural distribution circuits, which have exposure somewhat comparable to transmission systems.

3. Additional discharges below the limit of current sensitivity of the recording apparatus probably occurred. Also in case of two or more discharges through any single-pole arrester between successive inspections, only one current record would be obtained; hence discharges undoubtedly occurred without being recorded for this reason.

4. One three-pole arrester yielded a total of 29 single-pole records during the four-year period, and three others yielded 24 each.

5. The highest discharge current recorded through one pole of an arrester was 15,000 amperes. There is no reason for believing that this is the highest discharge current that can occur, and it is expected that as more data are accumulated, substantially higher currents will be recorded.

6. Arresters at certain locations were subjected repeatedly to high discharge currents.

7. Approximately 3.5 per cent of the arrester discharge currents were of 5,000 amperes or more.

8. The polarity of 87.6 per cent of the records was negative, and of 12.4 per cent was positive. The proportion of positive currents was lower than previously obtained for distribution arrester discharge currents and higher than for lightning currents in steel tower legs of transmission lines.

9. The difference in number of records obtained in different localities during the four-year period was as great as eight to one. An attempt to evaluate the factors that might have contributed to this difference, such as the number of thunderstorm days per year, types of line construction, line operating voltage, and the interval between inspections to locate magnetized links, did not account for this great a difference in severities. It is evident that the severity is influenced by the severity of the storms, including seasonal variations, and other local factors that can be determined only by experience, and cannot be accurately predicted on the basis of data obtained in other localities.

10. Any consistent trend which may have existed in the severity of discharge currents, as influenced by the circuit voltage rating, was obscured by the effects of other variables. It may be possible to evaluate this effect when more data are available.

11. Arresters connected to wood-pole lines without ground wires were subjected to more high-current discharges than other arresters. Discharges of 5,000 amperes or more occurred about ten times as often as with other types of line construction.

12. For arresters connected to wood-pole lines without ground wires, more than one pole of the arrester was involved in about two-thirds of the cases when discharges were recorded. For arresters connected to other types of lines, more than one pole of the arrester was involved in only about one-third of the cases.

13. The data indicate that increasing the number of lines connected to a station bus decreases the magnitude of the current which any one lightning arrester in the station is required to discharge.

14. In stations where there were several arresters so connected that they could discharge directly in parallel, the records obtained indicate that five arresters discharged in parallel on one occasion, three arresters in parallel on three different occasions, and two arresters in parallel on 24 different occasions. The individual arrester discharge currents were in general higher when two or more arresters discharged in parallel, than when only one of two or more arresters in a station discharged.

15. The data indicate that when a lightning current enters a station on a line equipped with a lightning arrester at the station entrance, the lightning voltages reaching other parts of the station are not usually sufficient to cause the operation of other arresters.

16. Damage to equipment at stations during this four-year investigation was of minor importance. The only lightning arrester which failed was of an old type, applied under compromise conditions. The five cases of bushing failure involved 22- or 33-kv bushings of obsolete design, the insulation of which appeared to have been in doubtful condition.

17. Calculation of the traveling-wave voltages associated with the recorded arrester discharge currents shows that for 11- to 33-kv lines, about 0.72 records per three-pole arrester per year, or 93 per cent of those recorded, represented lightning voltages that would have been dangerous to station equipment in the absence of arresters. Corresponding values for 44- to 88-kv lines are that 0.41 records per three-pole arrester per year, or 73 per cent of those recorded; and for 132-kv lines that 0.31 records per three-pole arrester per year, or 35 per cent of those recorded, would have been dangerous to station equipment in the absence of arresters. This clearly illustrates the relative number of lightning surges of dangerous magnitude which reach a station not supplied with lightning-arrester protection.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Electric Couplings

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Synopsis: Electric couplings have recently been applied on a large scale in geared Diesel ship drives to couple the engines to the gear. They serve a threefold purpose by acting as a flexible coupling to keep the torsional vibration of the engine out of the gears, as a disconnecting clutch to enable any engine to be cut out of service, and as an aid in maneuvering.

A typical large coupling built for marine service is described, and the general principles and characteristics of this type of device are given. Results of tests taken to confirm the calculated characteristics are included. The operation of the coupling as an aid in maneuvering is described. A summary of applications to date is given with a discussion of possible applications other than ship drive.

ELECTRIC COUPLINGS are devices for transmitting torque by means of electromagnetic forces in which there is no mechanical contact between the driving and driven members. Thus, they differ from electromagnetic clutches which are only friction clutches in which an electromagnet is used to apply the pressure between the friction surfaces. Electric couplings are not new in principle, but their application on a large scale has come only in the last few years. It is the purpose of this paper to review the principles of operation of electric couplings, describe their major application to geared Diesel-engine ship propulsion, and discuss the engineering problems associated with this application.

Probably the idea of an electric coupling is nearly as old as the idea of an a-c generator. There are a number of early United States patents from 1891 to 1906 describing at least the elements of the various types of electric couplings. In 1934 and 1935, the authors made a study of the various types of couplings with the hope of applying them to marine drives. Since 1935, A.S.E.A. in Sweden have equipped a number of ships with electric couplings.[1,2] A 3,000-horsepower coupling was supplied by the Westinghouse Electric and Manufacturing Company to the United States Navy and was quite thoroughly tested. At about the same time, two tankers were equipped with 750-horsepower couplings made by the Elliott Company. Within the past year, the United States Maritime Commission has purchased 116,000 shaft horsepower in electric couplings in 48 units to equip 20 vessels. The extent of electric coupling applications for marine service in this country is given by table I.

Principles of Operation

The electric slip coupling is the type used on all of the large marine applications, and the discussion of the numerous other types will be reserved till the end of the paper. The slip type has poles excited by direct current on one rotating member, and an armature winding, usually of the squirrel-cage type, on the other rotating member. If it is necessary to vary the speed, the winding can be insulated and brought out to slip rings, so that an external resistance can be connected in the circuit to vary the slip.[2] Any relative motion or slip between the two members will induce currents in the armature winding which react with the flux to produce a torque tending to hold the two members close together in speed. This is similar in action to the usual induction motor, except that the rotating field is produced by a direct current in a rotating member instead of by polyphase currents in a stator.

Application to Marine Drives

The principal application of the electric coupling is in geared Diesel-engine ship-propulsion drives as listed in table I. Other applications are described at the end of the paper. The arrangement of a typical marine application is shown in the sketch in figure 1. This is the arrangement being used on the four Maritime Commission *C*-3 cargo vessels listed as number 3 in table I. The four engines drive the single screw through four electric couplings and a two-pinion gear. The manner of mounting the couplings on the engine can be seen in figure 2, and the two members of the coupling are shown in figures 3 and 4.

The coupling performs four functions in the drive, as follows:

1. It acts as a torsionally flexible member between the engine and the gear, eliminating all shocks and limiting the transmission of torsional vibrations produced by the engine to a negligible amount.

2. Since there is no mechanical connection between the two members, the coupling permits a small amount of misalignment. This facilitates the erection of the propulsion plant and increases the reliability in service.

3. It acts as a quick-disconnecting clutch which is not subject to wear, and the torque of which is independent of speed. Any engine can be disconnected in less than a second by interrupting the field current of its coupling. This permits repairs to be made without stopping the ship, and some of the engines can be shut down at low speeds to give greater economy. The greater reliability of multiple-engine drives can be realized only if a disconnecting clutch is available to cut out a faulty engine, enabling the ship to proceed on the good engines. The use of the coupling as a clutch aids in maneuvering as described below.

4. The coupling limits the maximum torque to a safe value. The steady-state pull-out torque is usually about 150 per cent and the transient maximum torque on suddenly applied loads is about 200 per cent. If trouble develops on one engine, such as a seized piston, the electric coupling will limit the torque transmitted to this engine to twice the normal value, and will permit it to stop without injuring the gear and with minimum damage to the engine.

The ease with which electric couplings can be connected and disconnected en-

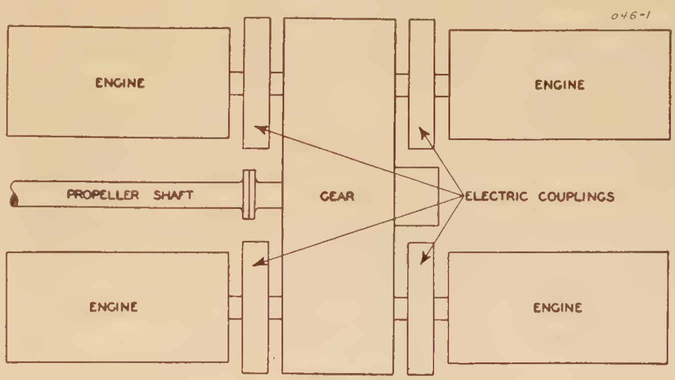

Figure 1. Arrangement of four-engine geared ship-propulsion drive for United States Maritime Commission C-3 cargo vessels, rated 8,500 shaft horsepower

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1. For all numbered references, see list at end of paper.

ables them to be used in maneuvering the ship in a manner which is impossible with other forms of couplings. When a large amount of maneuvering is to be done at low speed, as in going through a close channel or approaching or leaving the dock, the ship can be maneuvered entirely by the use of the couplings. This is done by running half of the engines ahead and the other half astern. The propeller can be connected to either group of engines by energizing the corresponding couplings, and the ship closely controlled by one coupling control lever. This system saves on starting air for the engines, and approaches the Diesel-electric drive in convenience.

The couplings can also be used to reverse the propeller in reversals from full ahead to full astern, as in a "crash stop". In such a reversal, the coupling excitation is removed and the engines reversed. After they are running on fuel at reduced speed in the astern direction, the coupling fields are energized, and the coupling torque reverses the propeller. Figure 5 shows a test slip torque curve on a coupling and a typical propeller torque curve during reversal,[3] assuming that the engines have been brought to 60 per cent speed in the astern direction before the couplings are excited again. It is evident from the curve that the coupling has sufficient margin in torque to reverse the propeller in a short time. This system of reversal is most advantageous on engines which do not have full torque available for reversal. By disconnecting the engine from the inertia of the gear, coupling fields, and propeller, they can be reversed very quickly, even with rather low torque available, because the inertia to be accelerated is low. With the engine on fuel, full torque becomes available to reverse the heavy inertias of the system and overcome the propeller torque. If the engine has sufficient reversing torque, the maneuvering can be done entirely with the engine, with the coupling acting like a solid coupling.

Characteristics

Losses. There are only three losses in electric couplings—windage, slip or armature I^2R loss, and excitation or field I^2R loss. The core loss is usually negligible, as the operating frequency is ordinarily less than one cycle per second. The core loss is included in the measured slip losses. The slip varies with speed and rating, but is ordinarily between one and 2 per cent. The field loss has about the same magnitude, so the efficiency varies from 95 to 98 per cent depending on the rating. The coupling illustrated in figures 1 to 4 tested just under 1.1 per cent slip and 97.75 per cent efficiency.

Torques. The torques required are determined by the operating conditions for the particular drive. The Maritime Commission engineers realized the full possibilities of using the electric coupling for maneuvering. They specified a minimum torque of 75 per cent for any slip up to 140 per cent to give the coupling some margin in torque over that required by the propeller during reversal. They also specified 150 per cent pull-out, or maximum torque as being sufficiently high to cover all conditions of operation. To obtain high torques at high slips, and at the same time maintain low slip at normal load and minimum weight and space, is a real design problem. Earlier couplings employed single-deck squirrel cages, although some of them used deep bars. The torques of these couplings at high slips were far below the values necessary to reverse the propeller at full ship speed. All couplings being built to the Maritime Commission specifications employ some

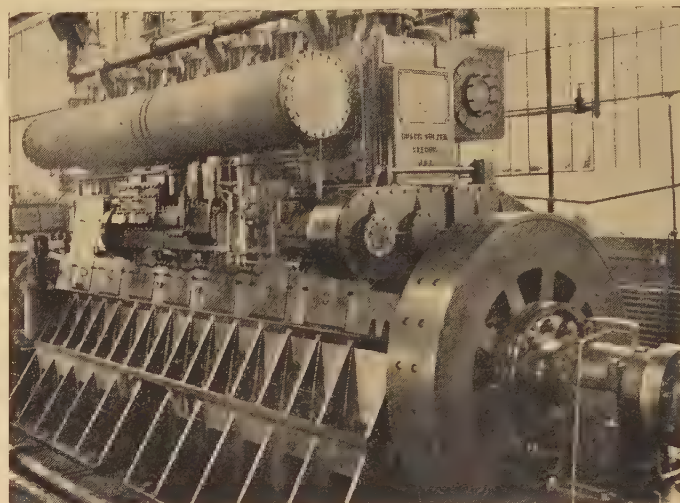

Figure 2. Electric coupling mounted on 2,225-horsepower, 240-rpm Diesel engine on shop tests

This is the engine and coupling for the drive in figure 1

Table I. List of Marine-Type Electric Couplings

Completed or Under Construction in United States of America, as of November 15, 1939

Number	Type of Vessel	Number of Ships	Ship Builder	Engines Per Ship	Engine Manufacturer	Engine Horsepower	Rating, RPM	Coupling Manufacturer	Gear Manufacturer
1**				1		3,000	400	W	
2	Tanker	2	C, M	2	F-M	750	400	E	F-B
3	†	1		1	Atlas	600	300	D	Falk
4*	*C*-3 cargo	4	Sun	4	Busch	2,225	240	W	Falk
5*	*C*-3 cargo and passenger	4	Sun	2	Sun	4,375	180	W	W
6*	*C*-1 cargo	5	ST	2	HOR	2,140	240	W	W
7*	*C*-1 cargo	5	W.P.&S.	2	Busch	2,085	233	E	F-B
8*	*C*-1 cargo	2	Penna	2	Nord.	2,105	220	W	W

* United States Maritime Commission vessels.
** Experimental unit for United States Navy. Not installed in a ship.
† The "Bear", Antarctic exploration ship, recently repowered for Byrd expedition.

Key to abbreviations:

C—Collingwood Ship Yards, Ltd.
M—Marine Industries, Ltd.
Sun—Sun Shipbuilding and Dry Dock Company
ST—Seattle Tacoma Shipbuilding Company
W.P.&S.—Western Pipe and Steel Company
Penna.—Pennsylvania Ship Yards

Atlas—Atlas Imperial Diesel Engine Company
Busch—Busch-Sulzer Bros. Diesel Engine Company
HOR—Hoover-Owens-Rentschler Division of General Machinery Corporation
Nord.—Nordberg Manufacturing Company
F-M—Fairbanks-Morse Company

W—Westinghouse Electric and Manufacturing Company
E—The Elliott Company
D—Dynamatic Corporation
F-B—Farrell-Birmingham Company
Falk—The Falk Corporation

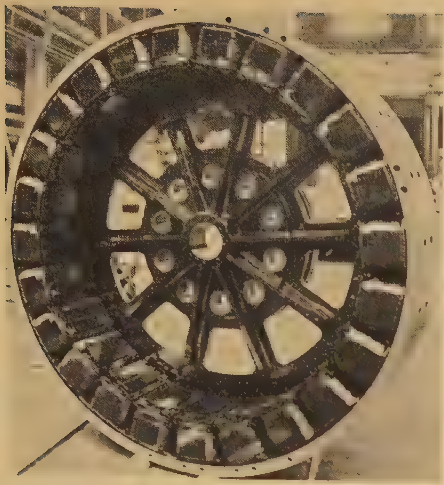

Figure 3. Field member of coupling shown in figure 2

form of double-deck squirrel-cage armature winding to increase the resistance at high slips.

Temperatures. All recent couplings have had guaranteed temperature rises of 70 degrees centigrade by resistance, above an ambient of 50 degrees centigrade. These are standard for class *B* insulation on electrical installations in ship engine rooms. This rise applies only to the field, as in the squirrel-cage type of armature there is no insulation, and the temperature is limited solely by mechanical considerations. It is customary to require that the coupling meet the guaranteed temperature rise when transmitting full torque down to 70 per cent of normal speed. This speed was chosen as it is the speed obtained with full torque on half of the engines, and was considered the most severe operating condition likely to be encountered. Theoretically, it would be possible to operate with full torque at half speed when running on one engine of a four-engine drive, but it was not considered that this would be an operating condition. With class *B* asbestos and mica insulation, the machine is practically incombustible and offers much less fire hazard than any device using oil.

Torsional Characteristics. In the cases studied so far by the authors, the electrical coupling has effectively limited the transmission of torsional vibration from the engine to the gears to negligible values. It has also had negligible effect on the critical speeds of the engine. In information previously published about electric slip couplings,[2] it has been said that the coupling does not transmit the torque pulsations originating in the engine. Strictly speaking, this statement is not exactly true, because as shown in appendix *A*, the electric coupling under the influence of pulsating torques acts as a weak elastic member, or a torsional spring of low spring constant. In appendix *B*, there is a further discussion of the effects of this spring constant, giving the reasons why it has negligible effect on the natural frequencies of the engine and at the same time effectively limits the vibrations transmitted from the engine.

Structural Features

The coupling illustrated in figures 2, 3, and 4 is typical of large marine couplings made in this country, especially those for Maritime Commission vessels. The two members are overhung on the gear and engine shafts. Most of the couplings have the inner member mounted on the engine shaft, but the coupling will transmit torque in either direction and the field can be put on the engine. The arrangement to be used depends largely on the amount of inertia desired by the engine manufacturer for satisfactory operation of the engine and the most advantageous placing of the critical speeds.

The field has the poles bolted to the inside of the rim of a fabricated-steel spider. The spider has a flange for bolting to the pinion shaft. The field is put on the outer member because such an arrangement gives more room for the winding, better ventilation, and more accessibility for replacing coils. The coils are made of edgewound copper strap with class *B* insulation of the same type almost universally used in large a-c motors and generators, representing the most rugged construction available. Repairs can be made quite easily by unbolting the pole, sliding it out axially, and installing a spare field coil. The collector rings are bronze and the collector assembly is split for ease of removal. The field is ventilated by air which is taken in through holes in the spider plate, passes axially along the windings, and is discharged at the open end.

The inner member consists of a fabricated spider which has a flange for bolting to the engine crankshaft flange. The core is made of one piece circular punchings shrunk on the rim of the spider. The winding is a double-deck squirrel cage with separate short-circuiting end rings for each layer. The outer layer of high-resistance bars is generously proportioned to absorb the heat produced during reversal of the propeller, since at high slips most of the loss is in the outer layer.

The coupling can be removed or assembled without disturbing the crankshaft or pinion shaft. Provision has been made to move the two members together axially a sufficient amount so that they will clear the spigot fits. In this position, they are centered together by a centering fit and can be bolted together. The entire unit can then be lifted out between the two shafts.

A screen guard is usually placed around the coupling for the protection of the engine room personnel. The brush holder parts are mounted on the gear case. The couplings take their excitation from the ship auxiliary power supply. The control consists of a selector switch operated by the coupling control lever at the engine control station, ammeters to indicate the field current, circuit breakers in each coupling circuit for short-circuit protection, and suitable magnetically operated contactors. Discharge resistors are provided and also a resistor to reduce the coupling field for long operating periods at low speed and low torque. The necessary interlocks are provided to prevent energizing a coupling when the corresponding engine is shut down.

The size and weight of a coupling of given rating increase quite rapidly with the air gap. The minimum gap which can be used is determined by the possible maximum unbalanced magnetic pull. The unbalanced magnetic pull acts in a radial direction and is proportional to the displacement for magnitudes of displacement encountered in normal operation. It acts to increase the displacement, so is equivalent to a negative restoring force.

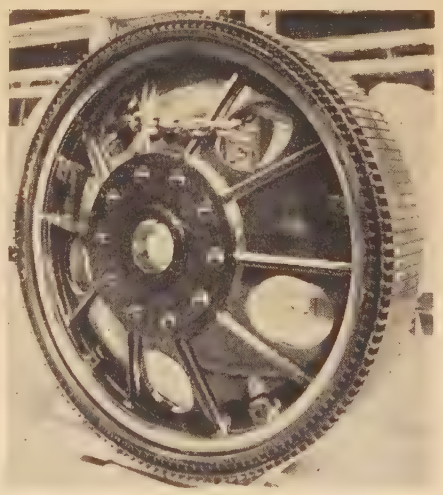

Figure 4. Armature or squirrel-cage member of coupling shown in figure 2

The magnitude of the force depends on the initial displacement which is a function of the bearing clearance, the accuracy of the original alignment, and the possible distortion or misalignment of the ship structure. With conventional

ship structure, the misalignment due to the distortion of the ship is very small, as a large deflection of the center of the ship with respect to the ends is produced by a small shear deformation. The air gap used represents a compromise between

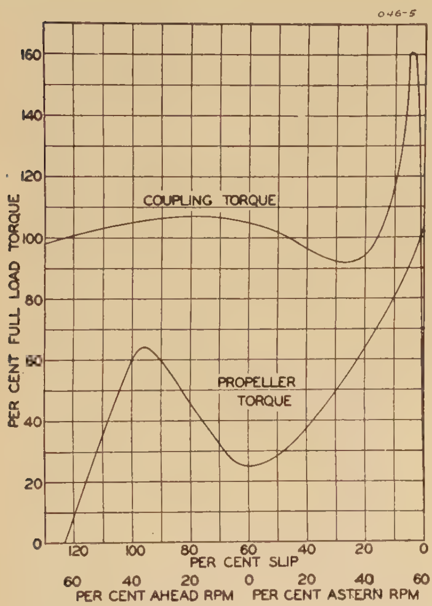

Figure 5. Test slip-torque curve of coupling shown in figures 1 to 4

A typical propeller-torque curve during reversal from full speed is shown assuming that the engine has been brought to 60 per cent speed astern before the couplings are excited

size and weight on the one hand and magnetic pull on the other. A gap of one-fourth inch appears to be a good compromise for large couplings. Since the magnetic pull may be increased by large bearing clearances, it is desirable to keep these clearances to a minimum consistent with good practice. It should be noted that the magnetic pull in an axial direction is very small.

Tests

Since the coupling described above was the first coupling to be delivered to the Maritime Commission, it was given rather extensive tests. The slip-torque curve was measured by locking one member of the coupling through a beam and scale and driving the other member at various speeds with a large d-c motor. The torque measured on the scale was checked by readings of the input to the driving motor. The results are shown in figure 5. The windage was measured by driving the coupling at various speeds and measuring the input. From the curve of friction and windage against speed, the windage could be separated out by the assumption that the friction loss varied directly with the speed while the windage varied as the cube of the speed. The ability of the squirrel cage to undergo a large number of maneuvering operations at reduced speed was demonstrated by locking the inner member, bringing the field member to 70 per cent speed with the excitation off, and then stopping it by applying the excitation. This was repeated 22 times in 9 minutes and 12 seconds with no injurious heating of the bars. Of course, there was no propeller torque to overcome, but the addition of the driving motor gave an inertia comparable to the final installation, and it was felt that the test demonstrated that the coupling had considerable margin above the requirements of actual service.

Further tests were taken on the coupling at the engine-builder's plant. The coupling was mounted on the engine as shown in figure 2, coupling it to a water brake. All of the regular tests on the engine were taken by loading it on the brake through the coupling. This also provided an opportunity for a full-load temperature test on the coupling, demonstrating that it met its guarantees with a good margin. The test setup included a flywheel on the brake side which was roughly equivalent to the mass of the gears and propeller in the final installation. The maneuvering of the ship was simulated, although it was not possible to include propeller torque, and the coupling was able to reverse the mass of its outer member and the flywheel from full speed ahead to full speed astern in from six to eight seconds. The tests indicated that some time in reversal of the propeller would be saved by reversing the engine independently with the coupling disengaged and then using the coupling to stop and reverse the propeller. Several torsiograph records were made to determine the amount of vibration transmitted through the coupling. Typical examples are shown in figure 6. The record marked *A* was taken on the engine crankshaft flange. The vibrations present are the seventh order, or the main firing frequency. They are speed variations rather than shaft vibrations. The record marked *B* was taken on the brake side of the electric coupling. None of the seventh order impulses can be seen on this record. The long swings are due to the natural period of the torsiograph. The high-frequency variations seem to have a frequency of 12 per revolution, and are probably excited by the brake. The amplification on the two records is about the same, record *B* being slightly higher than *A* as shown by the calibration for one degree indicated on the record. The revolution marked off in each record is the same revolution of the engine.

Other Types of Electric Couplings

There are as many possible types of electric couplings as there are types of motors and generators. The more practical types will be discussed briefly.

The slip coupling with squirrel-cage winding has been described in detail. For the purpose of obtaining variable speed, it is possible to insulate the armature winding and bring the leads out through slip rings exactly as in a wound-rotor induction motor. This type will be referred to as a wound-rotor coupling. The problem of controlling the speed through the external resistance is exactly the same as for the wound-rotor motor, except that it is possible to get fine speed adjustments

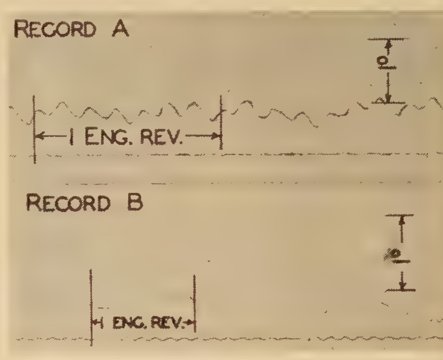

Figure 6. Typical torsiograph records, taken on shop test with engine driving water brake through electric coupling

Record *A* taken on engine crankshaft flange
Record *B* taken on output side of electric coupling

between resistance points by controlling the field current. The efficiency comes down nearly proportional to the slip. This type may find application to Diesel-engine drives where it is desired to run below the lowest operating speed of the engine.

A variable-speed coupling for certain types of load may also be obtained by designing a squirrel-cage slip coupling for high slip and controlling the torque by control of the excitation. This is analogous to controlling the voltage on a squirrel-cage motor. There are two difficulties in this: The high slip necessary for any appreciable range of slip by field control results in lower efficiency at full speed as well as at reduced speed. The other difficulty is the dissipation of the heat from the armature member, since all the slip losses go into this member.

Instead of a conventional squirrel-cage winding, it is obviously possible to use only a solid steel rotor on the armature, making use of the eddy currents induced in its surface. This type gives less pull-out torque and higher slip for the same air gap surface and weight. However, for variable speed by field control, it has the advantage that it can be arranged more readily to dissipate the high slip losses, especially in smaller sizes.

The inductor-alternator principle may be used to make an inductor-type electric coupling. The field is wound peripherally on one member, dividing the air gap into two sections. The flux is unidirectional in each section and is caused to alternate in the armature winding by the relative motion of inductor teeth on the other member. For a given air gap and pull-out torque, more air-gap surface is required in the inductor-type machine since the useful alternating-flux density is limited by saturation to about half of the value in a salient-pole type, due to the superposition of d-c and a-c components of flux. However, where the air gap can be kept very small, this type may result in somewhat cheaper construction for small couplings.

A synchronous coupling can be built by using salient poles and d-c excitation on both members. For most applications this type is less desirable than the slip coupling for several reasons. The increased excitation requirements partially offset the elimination of slip losses, and slip rings are required on both members. The synchronous "spring" torque tends to be higher than in the slip coupling, and if this type of coupling should pull out of step with fields excited, high values of slip-frequency alternating torque would be developed which might excite the torsional natural frequency of the connected mechanical system. Also the presence of field windings on both members makes it difficult to obtain high average torques at high slip.

Other Applications

The application of the slip type of coupling to geared Diesel ship-propulsion drives has been discussed in considerable detail, because that is the largest application of couplings made so far. However, it is interesting to note some of the other possible uses for couplings. This same type of coupling can be applied to any Diesel or gas engine where it is desired to limit the engine torque impulses transmitted to the load. It may also be used for the purpose of limiting the maximum torque and avoiding stalling of the engine. In such applications, the pull-out torque of the coupling must be made less than the stalling torque of the engine. It can be used as a disconnecting clutch to shift gears on an engine which is too large for a friction clutch.

The variable-speed coupling of either the wound-rotor or high-slip squirrel-cage type may be used with a synchronous motor or a constant-speed induction motor to obtain smooth speed or torque control. By use of field control, the speed can be controlled in finer steps than is practicable with a resistance in the secondary of a wound-rotor induction motor. As previously stated, the reduced speed is always accompanied by a reduction in efficiency, but this may not be too serious a handicap for a limited range in speed, for short-time operation at low speed, or for fan or pump drives where the power varies as the cube of the speed.

For a limited range of speed, or for a fan type of load, it is possible in the smaller ratings to obtain speed control entirely with field control of the coupling, using a slip type of coupling with high-resistance squirrel cage, or a solid steel armature.

Conclusions

The electric coupling has filled a definite need in the application of higher-speed Diesel engines to geared ship propulsion. The engineering problems encountered in this application have been satisfactorily solved, as proved by the installations which are now in successful service. As time goes on, a larger proportion of Diesel ship drives are being geared, and the percentage of these geared drives on which electric couplings are applied is increasing rapidly.

Now that the electric coupling has been developed and applied on a commercial scale, it is quite sure to find other applications where its characteristics can be used to advantage.

Appendix A

Electrical Torques Produced by Pulsating Motion in the Electric Slip Coupling

The analogy to the induction motor makes it apparent that the effect of the average torque is to produce a slip between the two members. The effect of any superimposed alternating motion between the two members is to produce both in-phase and quadrature components of alternating torque.

The component of torque in phase with the alternating component of the relative velocity is a damping torque, since it represents energy supplied by the alternating motion. The component of the alternating torque in phase with the angular motion (but opposite in direction) is a transient synchronizing torque, and is equivalent to a weak mechanical spring as far as alternating components of torque are concerned.

The mathematical analysis is based on the following assumptions:

1. That the field resistance is negligible in comparison with the field reactance at the frequencies to be considered.

2. That the squirrel-cage winding can be replaced by an equivalent two-phase winding. This has been proved by applications to induction motors to be quite accurate.

3. That the inductance (L) of these equivalent armature circuits is independent of the relative position with respect to the field. This, in general, is only approximately true, but the effects of variation in inductance will be analyzed further from a physical point of view.

4. The analysis will be carried through for a relative angular motion represented by $\theta=(\omega_s t+\theta_\Delta \sin \omega_\Delta t)$, where θ is the relative angular position of phase a with respect to the field, ω_s is the average angular velocity, θ_Δ is the amplitude of the alternating angular motion, and ω_Δ is 2π times the forced frequency of oscillation. All angles are measured in electrical radians. The actual alternating motion may not be sinusoidal, but it can be resolved into a series of sinusoidal components which can be treated in the same manner.

5. That the amplitude of the angular oscillation θ_Δ, is small, so that $\cos(\theta_\Delta \sin \omega_\Delta t)$ can be taken as unity and $\sin(\theta_\Delta \sin \omega_\Delta t)$ can be taken as $\theta_\Delta \sin \omega_\Delta t$. This is a good approximation up to about 15 electrical degrees. This maximum angle corresponds to about 50 per cent torque transmitted, which is higher than is likely to be encountered. On this basis:

$$\cos\theta=\cos\omega_s t+\frac{\theta_\Delta}{2}\cos(\omega_\Delta+\omega_s)t-\frac{\theta_\Delta}{2}\cos(\omega_\Delta-\omega_s)t$$

$$\sin\theta=\sin\omega_s t+\frac{\theta_\Delta}{2}\sin(\omega_\Delta+\omega_s)t+\frac{\theta_\Delta}{2}\sin(\omega_\Delta-\omega_s)t$$

The equation for voltage and current will be expressed first in volts, amperes, and ohms, and then the torque equation will be expressed in per unit notation in order to give both forms.

$$e_a=-p\left(\frac{M}{L_f}\psi_f\right)\cos\theta=\left(\frac{M}{L_f}\psi_f\right)\left[\omega_s\sin\omega_s t+\frac{\theta_\Delta}{2}(\omega_\Delta+\omega_s)\sin(\omega_\Delta+\omega_s)t-\frac{\theta_\Delta}{2}(\omega_\Delta-\omega_s)\times\sin(\omega_\Delta-\omega_s)t\right]$$

$$e_b=-p\left(\frac{M}{L_f}\psi_f\right)\sin\theta=-\left(\frac{M}{L_f}\psi_f\right)\times\left[\omega_s\cos\omega_s t+\frac{\theta_\Delta}{2}(\omega_\Delta+\omega_s)\cos(\omega_\Delta+\omega_s)t+\frac{\theta_\Delta}{2}(\omega_\Delta-\omega_s)\cos(\omega_\Delta-\omega_s)t\right]$$

The currents can be calculated by using the proper impedance for each frequency. The subscripts s, $\Delta+$, and $\Delta-$ will be used to indicate the impedances determined at frequencies $\frac{\omega_s}{2\pi}$, $\frac{\omega_\Delta+\omega_s}{2\pi}$, and $\frac{\omega_\Delta-\omega_s}{2\pi}$ respectively.

$$i_a=\left(\frac{M}{L_f}\psi_f\right)\left[\frac{\omega_s}{(Z_s)^2}(\gamma_s\sin\omega_s t-X_s\cos\omega_s t)+\frac{\theta_\Delta}{2}\frac{(\omega_\Delta+\omega_s)}{(Z_{\Delta+})^2}\left\{(\gamma_{\Delta+})\sin(\omega_\Delta+\omega_s)t-(X_{\Delta+})\cos(\omega_\Delta+\omega_s)t\right\}-\frac{\theta_\Delta}{2}\frac{(\omega_\Delta-\omega_s)}{(Z_{\Delta-})^2}\times\left\{(\gamma_{\Delta-})\sin(\omega_\Delta-\omega_s)t-(X_{\Delta-})\cos(\omega_\Delta-\omega_s)t\right\}\right]$$

$$i_b=-\left(\frac{M}{L_f}\psi_f\right)\left[\frac{\omega_s}{(Z_s)^2}(\gamma_s\cos\omega_s t+X_s\sin\omega_s t)+\frac{\theta_\Delta}{2}\frac{(\omega_\Delta+\omega_s)}{(Z_{\Delta+})^2}\{(\gamma_{\Delta+})\cos(\omega_\Delta+\omega_s)t+(X_{\Delta+})\sin(\omega_\Delta+\omega_s)t+\frac{\theta_\Delta}{2}\frac{(\omega_\Delta-\omega_s)}{(Z_{\Delta-})^2}\times\{(\gamma_{\Delta-})\cos(\omega_\Delta-\omega_s)t+(X_{\Delta-})\sin(\omega_\Delta-\omega_s)t\}\right]$$

In per-unit notation, the torque can be determined by the equation developed by R. H. Park[4] and others.

$$T=(i_a\psi_b-i_b\psi_a) \tag{1}$$

The per-unit currents can be obtained by dividing the actual amperes by rated amperes (I_0). The per-unit flux linkage, ψ_a and ψ_b can be obtained by dividing actual interlinkage by ψ_0 which is the flux linkage corresponding to the resistance drop at full load.

The net flux linkage of each armature circuit can be written:

$$\psi_a=\frac{1}{\psi_0}\left(\frac{M}{L_f}\psi_f\cos\theta+i_aL\right)$$

$$\psi_b=\frac{1}{\psi_0}\left(\frac{M}{L_f}\psi_f\sin\theta+i_bL\right)$$

Then

$$T=\left(\frac{M\psi_f}{L_f\psi_0}\right)(i_a\cos\theta-i_b\sin\theta) \tag{2}$$

Expanding this equation and neglecting all $\theta_\Delta{}^2$ terms because they are small for θ_Δ less than 15 degrees as assumed, and keeping impedances in ohms:

$$T=\left(\frac{M\psi_f}{L_f\psi_0}\right)^2\frac{\psi_0}{I_0}\left[\left\{\frac{\omega_s\gamma_s}{Z_s{}^2}\right\}+\left\{\frac{(\omega_\Delta+\omega_s)\gamma_{\Delta+}}{(Z_{\Delta+})^2}+\frac{(\omega_\Delta-\omega_s)\gamma_{\Delta-}}{(Z_{\Delta-})^2}\right\}\frac{\theta_\Delta}{2}\cos\omega_\Delta t+\left\{\frac{(\omega_\Delta+\omega_s)X_{\Delta+}}{(Z_{\Delta+})^2}+\frac{(\omega_\Delta-\omega_s)X_{\Delta-}}{(Z_{\Delta-})^2}-\frac{2\omega_sX_s}{(Z_s)^2}\right\}\frac{\theta_\Delta}{2}\sin\omega_\Delta t\right] \tag{3}$$

Using per-unit impedances, and using the symbols s and Δ to represent the per-unit slip frequency and forced frequency respectively, the torque may be written in per-unit notation:

$$T=(E_d')^2\left[\frac{\frac{\gamma_s}{s}}{\left(\frac{\gamma_s}{s}\right)^2+(X_s)^2}\right]+(E_d')^2\times\left[\frac{\frac{\gamma_{\Delta+}}{\Delta+s}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2}+\frac{\frac{\gamma_{\Delta-}}{\Delta-s}}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}\right]\times\frac{\theta_\Delta}{2}\cos\omega_\Delta t+(E_d')^2\left[\frac{X_{\Delta+}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2}+\frac{X_\Delta}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}-\frac{2X_s}{\left(\frac{\gamma_s}{s}\right)^2+(X_s)_2}\right]\frac{\theta_\Delta}{2}\sin\omega_\Delta t \tag{4}$$

In this equation, E_d' is the per-unit voltage proportional to $\frac{M\psi_f}{L_f}$, the flux which would link the armature if the circuit were opened and constant field flux, ψ_f maintained. In dealing with transient phenomena, this voltage would be called the voltage back of transient reactance.

From these torque equations, it is apparent that there is a steady torque dependent only on the average slip, s, and two alternating components, the $\sin\omega_\Delta t$ and $\cos\omega_\Delta t$ terms. The amplitudes of these alternating components are a function of the two frequencies $\Delta+s$ and $\Delta-s$. The sine term is in phase with, but opposed to the displacement and is, therefore, analogous to a weak mechanical spring connecting the two members. The magnitude of this spring constant is simply:

$$\frac{P(E_\alpha')^2}{4}\left[\frac{X_{\Delta+}}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2}+\frac{X_{\Delta-}}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}-\frac{2X_s}{\left(\frac{\gamma_s}{s}\right)^2+X_s{}^2}\right]T_0$$

Where P is the number of poles in the coupling and T_0 is rated torque. If T_0 is in pound-feet, the constant is in pound-feet per radian.

The cosine term is a torque in phase with the alternating component of the velocity, and is analogous to mechanical velocity damping. The damping coefficient is:

$$\frac{P(E_\alpha')^2}{4\omega_\Delta}\left[\frac{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)}{\left(\frac{\gamma_{\Delta+}}{\Delta+s}\right)^2+(X_{\Delta+})^2}+\frac{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)}{\left(\frac{\gamma_{\Delta-}}{\Delta-s}\right)^2+(X_{\Delta-})^2}\right]T_0$$

If T_0 is in pound-feet, the coefficient is in pound-feet per radian per second.

From the torque equation (2), it is seen that the pulsating components result from the action of the quadrature axis components of current ($i_a\sin\theta-i_b\cos\theta$). In order to simplify the derivation, the direct and quadrature axis reactances were assumed equal, but if they differ appreciably, the quadrature axis value should be used. If there are damping circuits on the field poles other than the field winding, they must be considered as affecting the reactance at the high frequencies.

Appendix B

Influence of the Electric Coupling on the Torsional Vibrations of the Propelling Drive

An important function of the electric coupling is to limit the transmission of torsional vibration from the engine to the gear. In the information published about electric couplings, it has often been stated that the electric coupling transmits only torques proportional to the slip, and therefore from the standpoint of torsional vibration separates the two systems on each side of it completely. As demonstrated in appendix A, this is not strictly true as the coupling acts as an elastic member having a spring constant which is a function of the frequency of the applied torque. It is zero at zero frequency and approaches a maximum value as the frequency increases. When a pulsating torque is applied to the coupling, a certain amount of energy is dissipated in the coupling. This energy acts as damping. For low frequencies up to one cycle per second, it is constant and equal to the torque normally produced in the coupling at normal slip, and then decreases rapidly as the frequency increases, being approximately inversely proportional to the frequency.

The electric coupling being located near the node of the vibration in the crankshaft, the damping in the coupling has very little influence on the amplitude of vibration in the engine. The damping in the coupling will be very effective in limiting the amplitude of low-frequency vibrations originating in the propeller if the nodes are such that large relative motions are produced in the coupling.

On high-speed Diesel engines, the low spring constant of the electric coupling has practically no influence on the natural period of torsional vibrations of the engine proper. Due to the small mass of the inner part of the electric coupling mounted on a very rigid crankshaft, this natural period is very high and only the critical speeds of high orders are in the operating range of the engine. Only an inappreciable part of these torque harmonics is transmitted through the coupling to the gears.

The effect of the spring constant of the electric coupling on the complete propelling drive is to produce a natural period of vibration of low frequency which might be in the range of the frequency of the torque impulses produced by the propeller blades cutting the wake of the ship. Usually, due to the large damping produced in the propeller, the vibrations thus produced are not dangerous unless they occur at the normal operating speed of the propeller. However, a thorough analysis of the complete propelling drive is advisable, making allowance for the spring constant of the electric coupling, to avoid any possibility of trouble.

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Discussion

Discussions will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Enclosed Spark Gaps

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Synopsis: Ionizing radiation has been discovered to be present in spark gaps of the type commonly used in commercial lightning arresters for the last 15 years. This radiation is emitted from discharges near the insulator-electrode contacts, when impulse voltage is applied to the gap. Ionization is produced by the absorption of this radiation in the spark gap. This effectively reduces the time lag of breakdown. The presence of this radiation explains why higher impulse breakdown voltages are obtained with a sphere gap in the dark than with a lightning-arrester spark gap with porcelain spacer. The radiation effect observed here is similar to that investigated by Wynn-Williams in the three-point gap. This paper tells of experiments performed to determine the reason for the low impulse ratios observed with rutile-spacer spark gaps. The results of this study explain the reason for the low impulse ratio of the "quench gap" and the "ionization gap" utilized in lightning arresters. This new information aids in understanding why low impulse ratios are obtained in high-voltage lightning-arrester spark gaps.

THIS PAPER describes experimental work which revealed a hitherto unrecognized, important factor responsible for the low impulse breakdown voltage found for short enclosed spark gaps such as are commonly used in lightning arresters. To obtain a low impulse ratio it has long been known that some form of ionizing radiation must be present.[1–4] In lightning-arrester spark gaps this radiation is emitted from subsidiary discharges discovered to exist between the electrodes and the insulating spacer, accompanying the dielectric displacement current. The intensity of this radiation may be expected to be proportional to the dielectric displacement current so that spark gaps with spacers of higher-dielectric-constant material, such as rutile,* give lower impulse ratios. This paper describes experiments made to study the interesting breakdown results obtained with rutile-spacer gaps. These tests led to the view that in lightning-arrester spark gaps the spark lag is reduced by radiation emitted

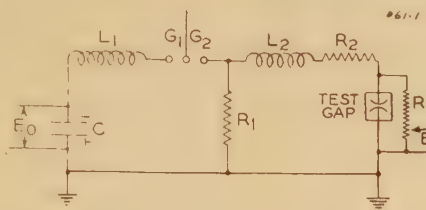


Figure 1. Impulse test circuit

C—One-fourth-microfarad capacitor
E_0—60,000 volts direct current
L_1—140 microhenries
L_2—75 microhenries
R_1—400 ohms
R_2—25 ohms
R_M—Resistance potentiometer
G_1, G_2—Synchronizing gaps
E_1—Voltage for oscillograph plates

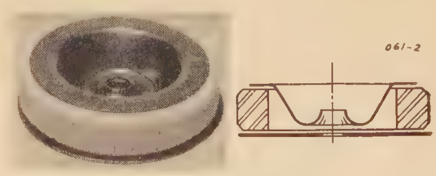
from the region of the contact junctions between the insulator and metal electrode. Practical application of this work has been made in the design of lightning-arrester spark gaps by utilizing common insulating materials with intensified radiation means.

Electrical Tests

The test circuit of figure 1 is commonly used for impulse tests on spark gaps. A capacitor bank, C, is charged to 60 kv, just below the breakdown potential of the double gap, G_1, G_2. The breakdown of G_1, G_2, is synchronized with the measuring circuits by means of a timed impulse applied to the middle electrode. The rate of increase of voltage over the test gap is determined by the circuit constants C, L_1, and R_1. After the breakdown L_2 and R_2 assist in regulating the magnitude and wave shape of the surge current. Breakdown potentials are reduced by a tapped noninductive resistor, R_m, for voltage measurements by a cathode-ray oscillograph. All impulse breakdowns were made on a front-of-wave-test in which the surge increased at the average rate of 50 kv per microsecond. This rate of rise is recommended by AIEE Standards No. 28 for arresters of six-kilovolt and under rating. Sixty-cycle breakdown tests were taken with a testing transformer having a calibrated third winding and an induction regulator in the low-voltage winding. In approaching the breakdown voltage the rate of increase of 60-cycle voltages controlled by the regulator is reduced so that if the breakdown lag is long, the time of voltage application is also comparatively long. Experiments have shown a small dependence of the 60-cycle breakdown upon radiation, particularly with polished electrode gaps. However, for the purpose of this paper comparisons are based on the measured 60-cycle breakdown values rather than the true d-c breakdown which is more difficult to obtain.

The procedure in testing a gap was to record eight impulse-breakdown tests at ten-second intervals immediately followed by eight 60-cycle breakdown measurements taken consecutively. The average impulse-breakdown value divided by the average 60-cycle crest breakdown determines the impulse ratio. The impulse ratio is used to compare gaps because of its lesser dependence on small differences in gap spacing. A rough indication of the accuracy on repetition of a gap is obtained by expressing in per cent the lowest and highest readings in the series of eight breakdowns as a fraction of the average value. The column in table I under the heading maximum and minimum consistency compares the various gaps in this way.

A typical enclosed spark gap, figure 2, has a disk and a shaped brass electrode separated by an insulating-ring spacer which completely surrounds the sparking



(A) (B)

Figure 2. Typical spark gap with porcelain spacer and metal electrodes

regions. The breakdown characteristics of this gap with the porcelain spacer are listed in table I, line *A*. When rutile ceramic was substituted for porcelain as the spacer material, the breakdown values measured are given in table I, line *B*. The main value of the rutile spacer previously anticipated was an improvement in voltage distribution over individual gaps in a multigap arrester. The lower im-

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* One common mineral form of titanium dioxide.

1. For all numbered references, see list at end of paper.

Table I. Average Breakdown Characteristics of Enclosed Spark Gaps With Disk and Shaped Electrodes of Figure 2

Line	Spacer	Total Number of Tests	Average Impulse Break-down	60-Cycle Average Break-down	Impulse Ratio	Per Cent Consistency Impulse Max.	Impulse Min.	60 Cycle Max.	60 Cycle Min.
A	Plain porcelain	120	13.0	7.5	1.75	114	81	103	95
B	Rutile ceramic	152	9.2	8.2	1.12	102.5	97.5	101.5	97
C	Leaded porcelain	128	9.5	7.7	1.23	108	93	102	95
D	1.65×10^{-6} g radium, plain porcelain	8	8.85	7.35	1.20	105	95	100	98

pulse breakdown obtained with rutile-spacer gaps was so surprising that an investigation was made of this phenomenon.

Rutile

Rutile is a common mineral and is one of the three crystalline forms of titanium dioxide. Powdered rutile can be molded and fired with or without the addition of bonding materials such as china clay. The important difference between rutile ceramic and porcelain is the high dielectric constant of the rutile ceramic. A dielectric constant of 80 to 100 has been measured for rutile ceramics used as spacer materials. Rutile retains its high dielectric constant at frequencies of 10^6 cycles per second.

Electrical discharges appeared at he spacer-electrode contacts during the breakdown tests. This contact voltage is illustrated in figure 3 where under similar conditions higher gradients exist over the air space when a rutile spacer is used. When highly conducting metal films were placed over the rutile spacer-electrode contact areas no change in impulse ratio resulted. Metal films on porcelain spacer contacts lowered the impulse ratio materially as indicated in line *C* of table I.

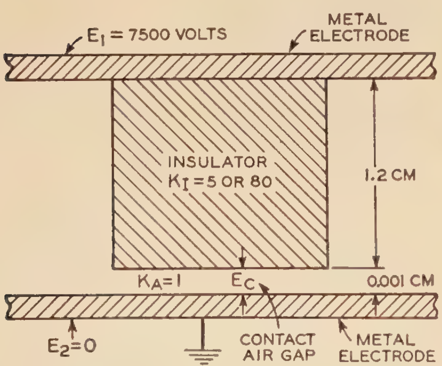

Figure 3. High gradients on assumed-contact air gap with porcelain and rutile spacers

Insulator	K_I(SIC)	E_c(Volts)	Gradient(Kv/Cm)
Porcelain	5	31	31
Rutile	80	470	470

The observed phenomenon with the rutile spacer gaps is similar to the effect of radiations from radium[5,6,7] and ultraviolet radiation[5,8] on the breakdown of spark gaps. Tests were made to see if the rutile contained enough radioactive materials to cause this improvement in impulse breakdown. The discharge rate of an electroscope was measured in room air, in close proximity to a rutile ceramic spacer, and with 1.65×10^{-6} gram of radium on a brass disk two centimeters from the collecting plate. The corresponding discharge rates were:

1. Air — 0.025 centimeter per minute
2. Rutile — 0.038 centimeter per minute
3. 1.65×10^{-6} grams radium — 150 centimeters per minute

A plain porcelain-spacer gap was tested with the radium-treated disk used in the electroscope tests and found to have a

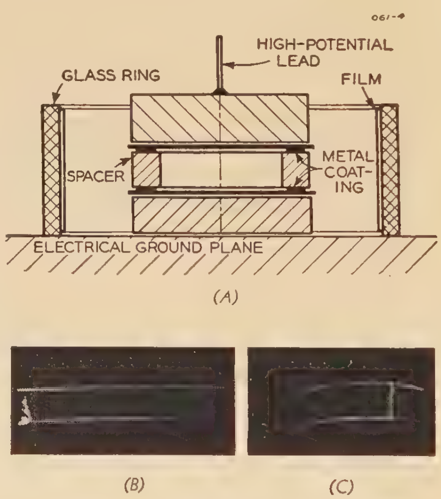

Figure 4. Dark-room tests

low impulse ratio of 1.2, table I, line *D*. It was concluded that the radioactive impurities in the rutile do not exist in sufficient quantities to cause the observed phenomena.

The possibility of the insulating surface emitting a radiation when electrically stressed was suggested and tests were made to see if such radiations were present. A rutile ceramic spacer with sprayed lead contacts was dipped into hot liquid ceresin wax, then cooled so that the entire surface of the spacer was coated with wax. The lead contacts on the rutile spacer were then scraped to remove the wax enough to make good contacts with the metal electrodes. In this scraping it is probable that some of the high-dielectric-constant spacer was exposed in the contact region. A low impulse ratio was obtained with the spacer insulating surfaces covered with ceresin wax. It, therefore, seems improbable that radiation from a stressed insulating surface causes the observed effect.

Barrier Tests

An attempt was made to interpose a barrier between the spacer-electrode junc-

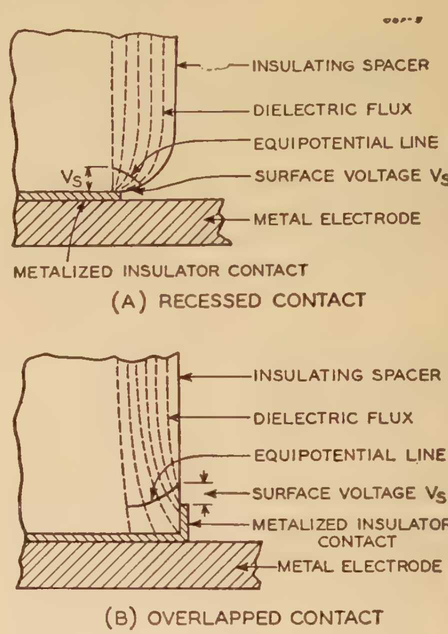

Figure 5. Potential over insulator surface near metalized contacts

tion and the central sparking region, by placing a loose fish-paper cylinder within the spark gap. At first low impulse voltages were obtained, but after changing the paper cylinder to a telescope construction, which was really light-tight, a high impulse ratio was obtained. When a $^1/_{64}$-inch-diameter hole was drilled through the otherwise opaque barrier, the impulse ratio was lowered.

Additional tests were made with picein wax covering the rutile spacer-electrode contact junctions on the inside of the spacer. When both of the electrode-insulator contact regions were covered with wax, high impulse ratios resulted. With only one contact region waxed, low impulse ratios were obtained. A contact layer of sprayed metal was brought up the inside of the rutile spacer and the con-

tact regions waxed but with a small ring of exposed lead extending beyond the wax. Tests showed low impulse ratios when the lead film was exposed.

Dark-Room Tests

A bare X-ray film was located around a rutile spacer with sprayed lead contacts and two disk electrodes as shown in figure 4*A*. No blackening appeared when this

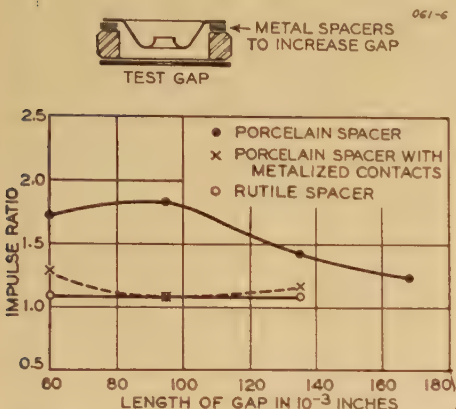

Figure 6. Variation in impulse ratio obtained by increasing gap distance while maintaining constant dielectric thickness

gap was energized at 7,500 volts, 60-cycle frequency, for several hours. One hundred short-time chopped surge waves of ten kilovolts crest gave no trace of radiation on the film. When the gap of figure 4*A* was excited to 8,000 volts crest at 540 kilocycles for one hour the X-ray film obtained is reproduced in figure 4*B*. The whole film was diffusely blackened but two intensely blackened lines appeared as a result of radiation from the contacts. A picture of the contact discharges was made with Zeiss camera (approximately *f*5) with a two-minute exposure in a dark room using the fastest available commercial film. The contact discharges were greatly amplified by increasing the voltage to just under the insulator flashover value. The picture in figure 4*C* shows some indication of the localized nature of the contact discharges. One flashover took place during the exposure and is visible in the picture. The two bands of light in the picture are the result of several points of light from contact discharges

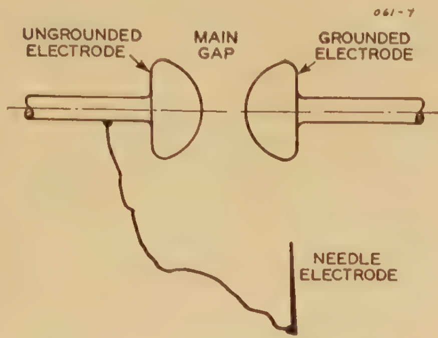

Figure 7. Three-point spark gap

that wandered around irregularly on the periphery of the rutile spacer at the lead-sprayed film outside edges.

Radiation From Contact Discharges

It is now obvious that the lower impulse-breakdown values obtained by the use of rutile spacers are due to a radiation in the gap coming from localized electric discharges at or near the inside contact junctions of the insulator and electrode. The radiation is present in abundant quantities to produce the effect through a $^{1}/_{64}$-inch-diameter hole. The discharges are attributed to stress concentrations and are present with highly conducting metal contact films. Two ways of producing stress concentrations with typical spacer shapes are shown in figure 5. It is not necessary to postulate imperfections in the surface of the dielectric to explain high air gradients. A metal contact film on the rutile spacer reduced the visible radiation intensity so that the contact discharges could not be seen in a dark room with careful observation under normal gap stress. Under this reduced visible intensity the impulse ratio was

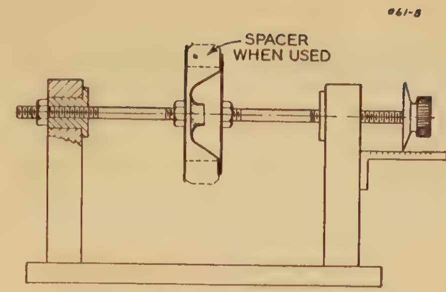

Figure 8. Externally supported spark gaps

equally low. In the case of porcelain spacers the lead contact films definitely lowered the impulse ratio. This is attributed to the more favorable location of the radiation source on the porcelain.

That porcelain spacers may be made to radiate with greater intensity so as to lower still further the impulse ratio was proved by testing the porcelain gap at increased gap spacings which effectively increased the working stress of the porcelain. In the curves of figure 6 are plotted the impulse ratio as a function of the gap spacing where the gap spacing was increased by the addition of metal-ring spacers on top of the various insulating spacers. At about three times the normal gradient the plain porcelain spacer gap has an impulse ratio of 1.2.

The Three-Point Spark Gap

The impulse breakdown potential of a spark gap can be lowered by the three-point effect first explained by C. E. Wynn-Williams[9] in 1926. A typical three-point gap is reproduced in figure 7. When the sharp point of the needle was placed within six centimeters of the ungrounded electrode and electrically connected to it so that it was "visible" to the gap, a lower surge breakdown voltage was obtained. All barriers when placed in front of the point neutralized this effect except a specially prepared thin celluloid film. The effect was obtained in a dark room where no discharge could be seen to pass

Table II. Tests With Electrodes Supported Externally—Figure 8

Spacer	Electrodes	Gap (Mm)	Surge Breakdown (Kv)	60-Cycle Breakdown (Kv)	Impulse Ratio	Average Surge Gradient (Kv/Cm)	Average 60-Cycle Gradient (Kv/Cm)
None—open to room	Brass disk and shaped	1.65	14.5	8.84	1.64	88	53.5
None—in light-tight box	Brass disk and shaped	1.65	17.6	9.42	1.87	107	57.0
Plain porcelain	Brass disk and shaped	1.65	13.2	7.68	1.72	80	46.5
Leaded-contact porcelain	Brass disk and shaped	1.90	10.8	7.93	1.36	57	41.7
Leaded-contact rutile	Brass disk and shaped	2.11	9.08	8.48	1.07	43	40.2
None—open to room	3.8-cm brass* polished spheres	1.65	14.5	9.64	1.50	88	58.3
None—in light-tight box	3.8-cm brass* polished spheres	1.65	24.4	9.29	2.63	148	56.3

* One hour between polishing and testing.

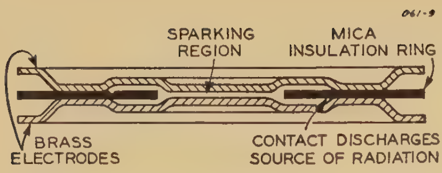

Figure 9. Unit of quench gap, lightning-arrester spark gap which utilizes ionizing radiations from contact discharges

Average impulse ratio of unit quench gap = 1.05

from the needle point to an electrode. His conclusions were that:

"1. Before the three-point phenomenon can be obtained some form of discharge, silent or spark, must be 'visible' from the main gap and within a certain distance of it.

"2. The phenomenon is obtained in the absence of:

"(a). Disturbance of the electric field near the main gap and

"(b). The passage of ions from the pilot discharge into the main gap.

"3. A radiation is emitted by the pilot discharge which can ionize the gas in the main gap.

"4. When this radiation is prevented from reaching the main gap the usual three-point effect is not obtained.

"5. The three-point effect is still produced when the electrodes are so shielded as to prevent any photoelectric effects...

"6. The observed properties of this radiation seem to establish the limits of its wave length as being approximately 13 to 1,000 angstroms, and they coincide to a large extent with the corresponding properties of *entladungstrahlen*."

As these conclusions so thoroughly explain the rutile-spacer spark-gap tests, it seems safe to conclude the same phenomena must be present in both cases.

Recent Work

H. Rather[10] has measured the absorption coefficient of similar radiation from a spark discharge. He believes the gas-ionizing radiation to be between the limits of 800 to 1,000 angstroms. By means of a Wilson cloud-chamber apparatus he has measured and extrapolated the absorption coefficient of the effective radiation from sparks to be $\mu=2$ for air, $\mu=0.8$ for hydrogen, and $\mu=5$ for oxygen, at 760-millimeter pressure.

Mounted-Electrode Tests

To observe the performance of a gap without short insulating spacers the disk and shaped electrodes were mounted on an adjustable micrometer spark gap as shown in figure 8. The electrode sparking surfaces were first polished, cleaned, and then roughened with fine alundum paper. The roughening process was repeated before each set of tests. The gap spacing was set equal to that of the porcelain gap of figure 2, and tested with the electrodes open to room air. The impulse ratio measured was 1.64 with 60-cycle and impulse voltages as shown in table II. When the same gap was placed inside a light-tight maplewood box the impulse ratio rose to 1.87. The higher impulse ratios in the light-tight box are attributed to a decrease of radiation. When the spark gap is open to room air, possible sources of radiation are corona points on the surge generator, radioactive material in the room, atmospheric radiations, and incandescent filaments.

With a plain porcelain spacer inserted between the electrodes of figure 8, the impulse ratio measured was 1.72. As the porcelain spacer makes the gap relatively light-tight some radiation must be present normally in the plain porcelain gap. The lower breakdown gradients recorded in table II for this test are added evidence of radiation. When a sprayed-lead porcelain spacer was tested in the same gap structure the impulse ratio was 1.36. This low value is attributed to a more favorable location of the radiation present in the porcelain-spacer gap. A leaded rutile spacer in the same gap structure gave an impulse ratio of 1.07. The breakdown gradients are low, indicating a greatly increased intensity of radiation.

Two 3.8-centimeter spherical electrodes were mounted in the micrometer support and tested open to the room and in the dark box. The results listed in table II show a similar increase in impulse ratio for spherical electrodes in the light-tight box.

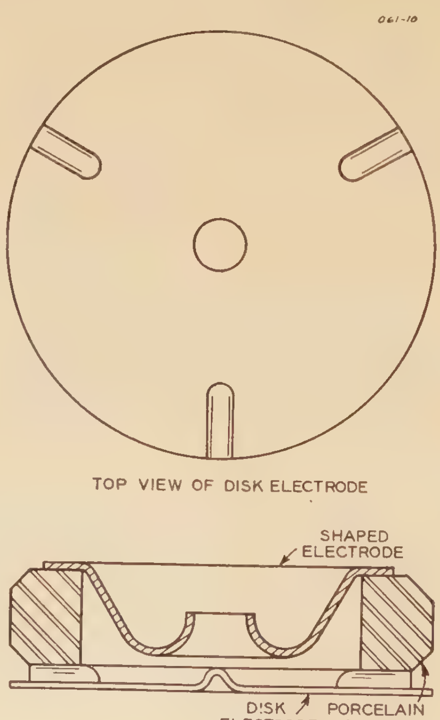

Figure 10. "Ionization" gap

Average impulse ratio of single ionization gap = 1.2

Applications

A single unit of the "quench gap" construction[11] is shown in figure 9. In this gap effective radiations are emitted from the mica insulator and electrode-contact region. Some of this radiation penetrates into the sparking region and effectively lowers the time lag of breakdown.

In the "ionization" gap sketched in figure 10 the disk electrode has been raised in three locations. Contact with the porcelain spacer is made on these three raised lands. The air in the region of the porcelain-disk contact is stressed sufficiently on rapid voltage rises to cause the sparking region to be irradiated as in the "quench gap."

Conclusions

The impulse ratio of spark gaps with spacings of between one and two millimeters depends upon the radiation present in the gap. An effective radiation is present in the usual porcelain-enclosed gap used in lightning arresters. This radiation is emitted from electrical discharges at the insulator-electrode junctions. A high-dielectric-constant spacer gives low impulse ratios, probably because the intensity of the effective radiation is proportional to the displacement current in the insulator. The wave length of the most effective part of a similar radiation was determined by Wynn-Williams in a study of the three-point spark gap as lying between 13 and 1,000 angstroms. Experiments in this region of the soft X-ray spectrum are difficult due to rapid air absorption.

The discovery of this radiation in porcelain-enclosed spark gaps explains why porcelain space gaps have lower impulse ratios than plain spark gaps of the same spacing in the dark. The results of this study fully explain the reasons for the low impulse ratios obtained in the "quench gap" and the "ionizing gap" which are both utilized in commercial lightning arresters.

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Water Solution in High-Voltage Dielectric Liquids

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IT HAS long been recognized by the practical engineer responsible for the proper maintenance of high-voltage oil-filled electrical equipment that water constitutes one of the chief and in some instances the only serious threat to successful service. However, consideration of the dangers presented by water during the operation of high-voltage machines must not be limited to a study of the relation between the dielectric strength and the water content of the insulating liquid used. For successful operation, the cellulosic insulation must be maintained in a dry condition. Water in such dielectrics leads ultimately to insulation failure. One of the first lines of defense against this disastrous result is the adequate drying of the solid dielectric in the factory manufacture of the equipment. Just as important, however, is the clear recognition that cellulosic insulation may be brought to a hazardous condition in service by water absorption from the surrounding atmosphere through the insulating liquid. The sorption of moisture by cellulosic insulation in this manner is of importance to all types of liquid-treated electrical apparatus but is of especial importance to liquid-cooled transformers in which the circulation of the liquid, carefully factored into the design for cooling purposes, so effectively presents a continuous supply of dissolved moisture to the hygroscopic insulation of the windings.

The dielectric-strength test of insulating liquids has long been accepted as an adequate protection against dielectric deterioration produced by water, but such a test as used in practice gives no adequate protection against the insidious penetration of water and its sorption by the cellulosic insulation. The practical dielectric strength represents the summation of many deteriorating effects, including the effect of fibers, dust, and other suspended or dissolved materials. The effect of these materials becomes greatly pronounced in the presence of water[1–4] and their prevalence in normal commercial practice has necessitated the establishment of dielectric-strength standards of such value that dissolved moisture may unsuspectedly be present in an amount which, because of its continuous transfer to the liquid-immersed cellulose insulation, may be sufficiently large seriously to affect the insulating properties of the latter and to present a dangerous condition for commercial use.

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1. For all numbered references, see list at end of paper.

A Laboratory Test for Quantitatively Determining the Amount of Dissolved Water in Insulating Liquids

A number of test methods have been suggested for quantitatively determining the amount of water dissolved in mineral oil and other organic liquids.[5] The method adopted in this study has been a modification of the procedure suggested by Smith and Bryant,[6] the water content being expressed in parts per million by weight.

Dry nitrogen gas is bubbled through 500 to 1,000 grams of the carefully weighed insulating liquid at 130 degrees centigrade for a period of three hours. From the insulating liquid the nitrogen gas is led through two liquid-air traps where the entrained moisture is removed. The frozen condensate in the traps is dissolved in 25 cubic centimeters of dry acetone and slowly added to a cold acetyl chloride-pyridine mixture. In the preparation of this mixture, 10 cubic centimeters of acetyl chloride dissolved in dry benzene (118 grams per liter of solution) are contained in a dry 250-cubic centimeter glass-stoppered flask and cooled in an ice bath. Two cubic centimeters of dry pyridine are added dropwise to the acetyl chloride solution with continual shaking. A white precipitate of acetyl chloride-pyridine complex is formed.

After the slow addition of the acetone condensate solution to the ice-cold acetyl chloride-pyridine complex has been completed, the mixture is removed from the ice bath and allowed to stand at room temperature in diffused light (not in direct sunlight) for at least 15 minutes, but not more than 30 minutes, after which 20 cubic centimeters of dry ethyl alcohol are slowly added with continuous shaking. After a further standing at room temperature for five minutes, the solution is ready for titration with 0.5 *N* sodium hydroxide solution using phenolphthalein indicator.

A blank run is made simultaneously with the sample, using completely duplicate conditions except that no frozen distillate is added. This allows correction to be made for errors due to moisture inadvertently present.

In the actual application of water-testing procedures for insulating liquids, mineral oil is one of the more important insulating liquids tested. As is well

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Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

known, this material will be found in commercial apparatus in all stages of oxidation. This oxidation results in the formation of volatile acidic materials. Such products entrapped in the refrigerated tubes of the water-testing apparatus, will in themselves react with acetyl chloride or the sodium hydroxide used for the titration and produce erroneous results. For mineral transformer oils in normally good condition, the correction factor is negligible but for oils in the higher stages of oxidation a correction in the water content value must be applied. This correction corresponds to 7.3 parts per million of water content for each 1.0 milligram of potassium hydroxide per gram of oil used in the acidity titration.

The Solubility of Water in Dielectric Liquids

The amount of water dissolved by a liquid is a function of the chemical nature of the liquid itself and the conditions to which it is exposed. In the case of mineral insulating oil, the degree of refining and the previous oxidation to which it has been subjected are factors of real importance. Figure 1 illustrates the effect of refining treatment on the solubility

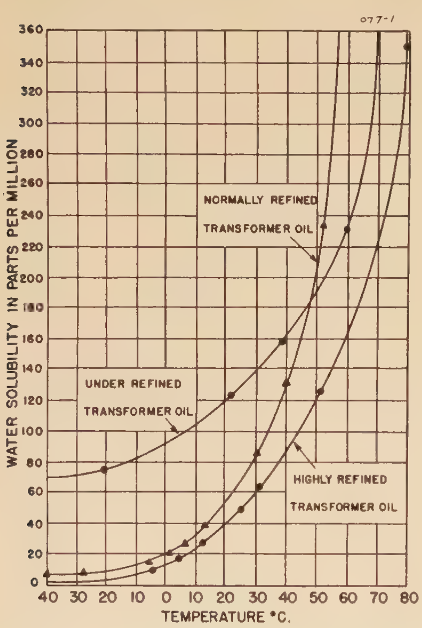


Figure 1. The solubility of water in mineral transformer oil and the effect of the refining treatment

of water in mineral transformer oils of low cold test.

In the use of mineral oils, oxidation effects must not be ignored when water-solubility problems are considered. Oxidation promotes the emulsification of water and leads to increased water solubility in the oil. Unless otherwise stated, only new, unoxidized mineral oils are used throughout this paper.

Synthetic, noninflammable, dielectric transformer liquids in commercial use are the chlorinated derivatives of the benzenoid hydrocarbons. These compounds are characterized by a high re-

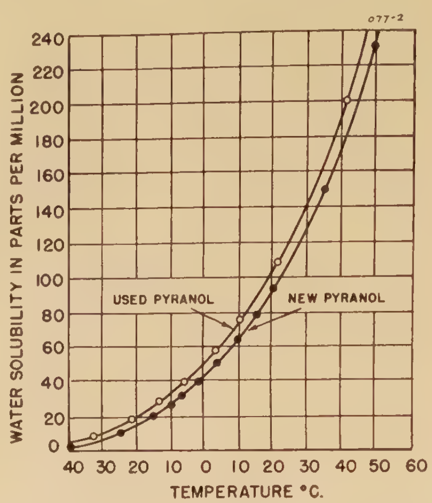


Figure 2. The solubility of water in transformer Pyranol

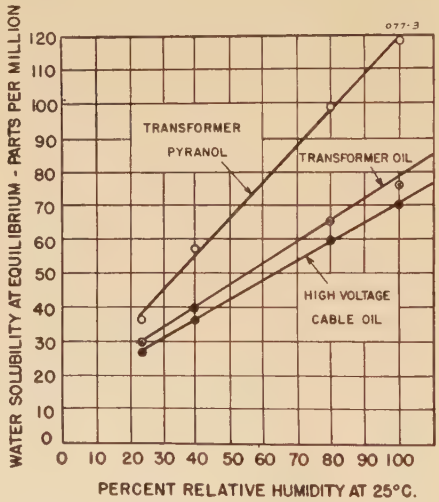


Figure 3. The maximum amount of water absorbed by transformer and cable insulating liquids exposed to humid air

sistance to oxidation and are, therefore, not susceptible to changes in water solubility during use. This fact is demonstrated in the data of figure 2 which describe the solubility of water in new and used Pyranol.

The Hygroscopicity of Dielectric Liquids

The data presented in figures 1 and 2 are of interest and importance in indicating the limiting values of solubility beyond which water cannot accumulate in the liquid without visible cloud formation. Such values, however, give no indication of the sorptive ability of the

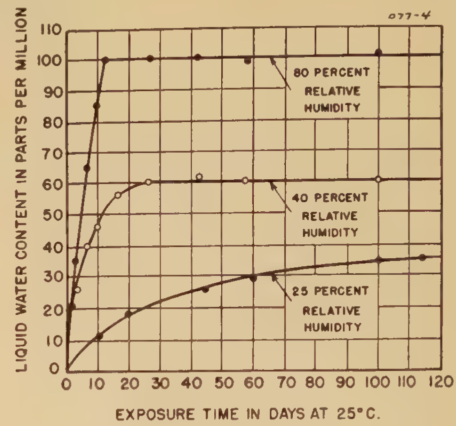


Figure 4. The absorption of water from humid air by transformer Pyranol

liquid when exposed to less than water saturated atmospheres as in normal handling and use.

Figure 3 illustrates the water solubility in transformer liquids at equilibrium with air, the water content of which is expressed in the commonly used terms of relative humidity. Figure 3 also compares the water sorptive characteristics of a typical, American, Pirelli-type, high-voltage mineral cable oil. The comparative Saybolt Universal viscosity values at 37.8 degrees centigrade for the three liquids are:

Transformer Pyranol.........	55 seconds
Transformer mineral oil.......	58 seconds
Pirelli cable oil...............	100 seconds

The water equilibrium set up by an insulating liquid and the air with which it may be in contact is of importance in many commercial uses. In the handling of insulating liquids, however, it is also important to know the rate at which water is taken up by liquid. This is an extremely difficult practical problem since the speed with which a liquid approaches its water equilibrium condition is dependent on a large number of empirical factors, prominent among which is the intimacy of contact between the liquid and the humid atmosphere from which the water is taken. Large surface exposure produced by liquid circulation or other means accelerates water absorption. Figures 4 and 5 illustrate the rate of water absorption for mineral transformer oil and for transformer Pyranol exposed to air of different humidities. In this work the liquids were exposed in a

quiescent state under the following conditions:

Volume of liquid, 7,500 cubic centimeters
Surface area exposed, 375 square centimeters
Liquid depth, 20 centimeters
Temperature of exposure, 25 degrees centigrade

The rate at which water is taken up by mineral oil is but little affected by those physical and chemical changes accompanying increased oil viscosity. This is illustrated in the data of figure 6 which compare three mineral oils of the Gulf Coast crude type, with viscosities which range from 58 seconds to 195 seconds Saybolt Universal at 37.8 degrees centigrade.

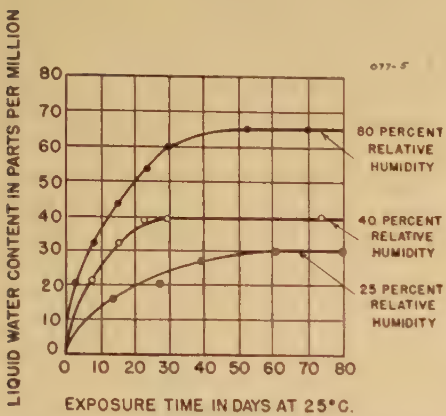


Figure 5. The absorption of water from humid air by mineral transformer oil

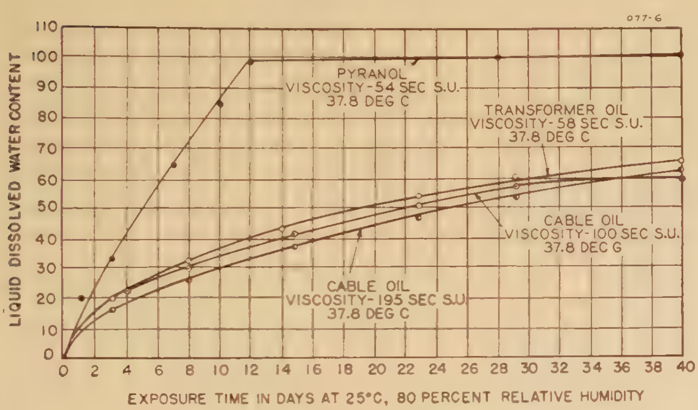


Figure 6. Comparing the water absorption by insulating liquids of different viscosity when exposed to humid air at 25 degrees centigrade

The Transmission of Water Through the Insulating Liquid and Its Sorption by the Cellulosic Insulation Immersed Therein

Cellulose has been described as a very hygroscopic material whose ability to absorb water is comparable to even the best of chemical desiccants.[7] It is, therefore, not unexpected to find that dry cellulose immersed in wet oil, reduces the water content of the latter. The rate at which the water is transferred from wet oil to the dry cellulose depends on factors similar to those which apply in the transfer of water from humid air to dry oil. Chief among these is the intimacy of contact between the cellulose fiber and the oil. Factors causing oil circulation, thus bringing a continuous supply of wet oil into contact with the paper insulation of a typical transformer-coil winding, will accelerate the moisture removal from the oil. Figure 7 illustrates the water transfer for one specific setup in which the dried cellulosic insulation was immersed in wet transformer liquid maintained without circulation at 25 degrees centigrade.

The data of figure 7 were obtained by humidifying the transformer liquid at 25 degrees centigrade. Kraft insulating paper (0.001 inch) was dried at 110 degrees centigrade under a pressure of 0.3 millimeter of mercury for 24 hours. The dry paper weighed 40 grams and was in the form of a cylindrical tube. The vacuum-dried paper, approximately 15 square feet in area, was immersed in 1 1/2 quarts of the wet liquid contained in a two-quart sealed, glass container which was allowed to stand without agitation. Samples of the liquid were withdrawn at frequent intervals for measurement of the dissolved water content.

Figure 7 is of value in indicating the rapidity with which dry cellulosic insulation will absorb moisture from the wet insulating liquid of a transformer. In obtaining the data of figure 7, it must be emphasized that there was a limited supply of water available that held by the insulating liquid. As the water was removed from the latter, its water content dropped until after about four days for the mineral transformer oil and 16 days for the transformer Pyranol an equilibrium was established between the water-in-liquid and water-in-cellulose condition. This equilibrium was substantially independent of the nature of the insulating liquid.

Figure 8 illustrates the water transfer occurring when wet insulating paper is immersed in dry transformer liquids. These data were obtained during a test run in which 40 grams of paper, prepared by exposure for 48 hours to air at 70 per cent relative humidity, 32 degrees centigrade, were immersed in the shape of a cylindrical tube in 1 1/2 quarts of dry insulating liquid, maintained throughout the test in a sealed container at 25 degrees centigrade. It is obvious from the data of figures 7 and 8 that the direction of water transfer, whether from liquid to cellulose or cellulose to liquid, is dependent on the relative moisture content of the materials involved.

In a sealed container, once the equilibrium condition is reached between the water content of the cellulose and that of the insulating liquid, it cannot be considered in an easily changed condition. This is illustrated in the data of figure 9. Here the 25-degrees-centigrade data of figure 7 for dry paper in wet mineral transformer oil and that of figure 8 for

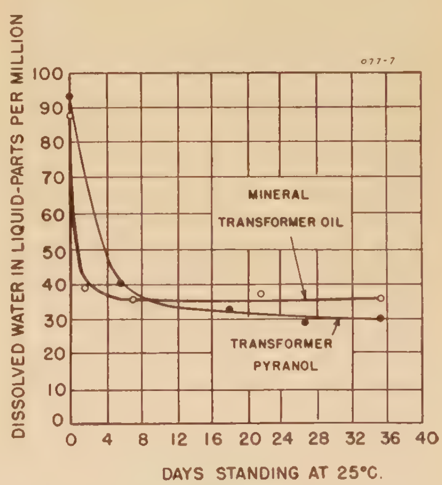


Figure 7. The dehydration of wet insulating liquids as a result of moisture absorption by dry cellulosic insulation immersed therein

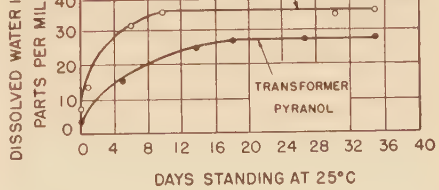


Figure 8. The absorption of water by dry insulating liquids in contact with cellulosic insulation previously exposed to humid air

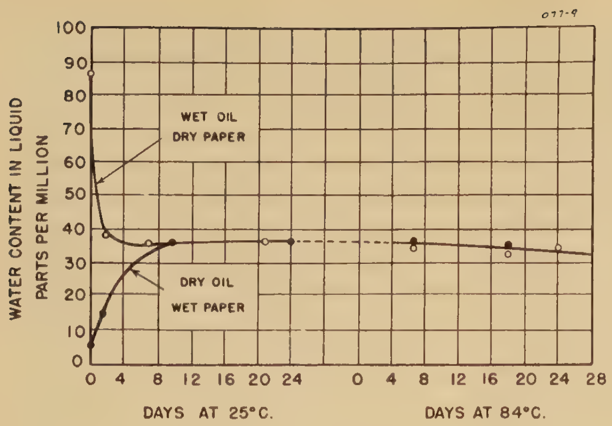


Figure 9. The characteristics of the moisture equilibrium set up between mineral transformer oil and the impregnated cellulose insulation

wet paper in dry mineral transformer oil are plotted together. After the common equilibrium has been established, each setup is heated from a 25- to an 84-degree-centigrade liquid temperature. The equilibrium is substantially unchanged. This behavior is of real importance in transformer practice for it indicates the danger which results when moisture is allowed to be dissolved by the insulating liquid. When once the moisture is absorbed by the impregnated cellulose, unless it be present in abnormally large amounts, it is released again only by drastic treatment which involves the application of temperatures in the range of 95 to 100 degrees centigrade and higher.

The practical application of the data describing the absorption of water from wet oil by dry cellulose is made extremely difficult because of the importance of surface contact in determining the final equilibrium value. This is demonstrated in a series of tests in each of which is used the same amount of oil having the same initial water content. In each test, however, the amount of dry paper immersed in the oil is changed both in respect to the quantity present and the surface area exposed. In one setup two grams of vacuum-dried 0.001-inch kraft paper were immersed in the oil so that the total surface area of 1.50 square feet was entirely bathed by the liquid. In a second setup, 40 grams of the same vacuum-dried paper with a total surface area of 30 square feet were assembled in a cylindrical-shaped roll and immersed in the oil so that only the outer roll surface and ends were exposed to direct contact with the oil. An equilibrium was established between the paper and the oil in each case. With only two grams of well-exposed paper, 0.0082 grams of water was absorbed per gram of paper. With the compact roll assembly containing 40 grams of paper, only 0.0014 gram of water was absorbed per gram of paper.

The Dehydration of Insulating Liquids

In the data already presented, it will be observed that in no instance has the presence of initially dry paper been able

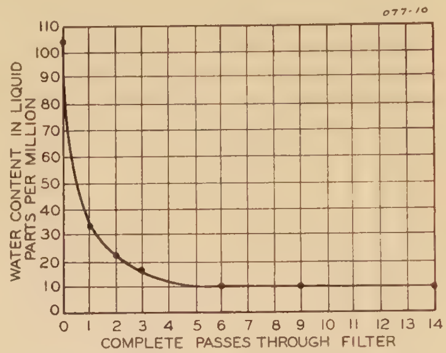


Figure 10. The dehydration of transformer Pyranol by means of paper filtration at 25 degrees centigrade with frequent changes of the filtering papers

Used papers were replaced at the time of each test value indicated

to reduce the water content of the dielectric liquid to zero. An equilibrium is ultimately set up which recalls the equilibrium generally recognized to exist between the water content of paper and of air. In the drying of cellulosic insulation, it is necessary to upset this equilibrium which is done in common practice by the use of heat and vacuum. The fact that an equilibrium also exists between water-in-liquid and water-in-cellulose indicates clearly that under some conditions as for example in the data of figure 8, the cellulose may impart water to the liquid. In like manner, an improperly dried blotter paper used in the filter-press treatment of the dielectric liquid, although removing suspended particles, may even lead to an increased oil-dissolved water content. It is further obvious that unless completely dried filter papers are successively supplied in the filtering treatment, the equilibrium ultimately established may prevent the lowering of the water content of the liquid to the desired safe value.

Water in solution in mineral insulating oil or other dielectric liquid is removed only by careful and severe treatment. Figure 10 illustrates the difficulty of removing dissolved water from transformer Pyranol using a standard seven-inch blotter press. Despite the extensive use of new, dry filter papers, it was impossible to lower the dissolved water content of the Pyranol below ten parts per million.

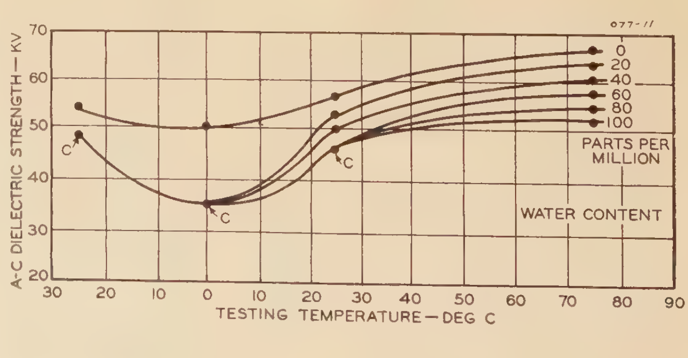
A modified filter press has been designed[8] which incorporates frames much deeper than those of the usual plate and frame press. These deeper frames give spaces which are filled with 80/300-mesh fullers earth. In the standard seven-inch press, sufficient capacity is provided for about one gallon of the fullers earth. With such a "fullers earth" press, equipped with well-dried blotter papers of the usual type, complete liquid drying is more easily obtained. Using 30 gallons of Pyranol containing 116 parts per million of dissolved water, and a filter containing fullers earth previously dried at 200 degrees centigrade, the water content of the Pyranol in parts per million is decreased as follows:

Initial water content	116
After one pass through filter	9
After one-half hour circulation through the filter	0

It is customary in some instances to

Figure 11. The rapidly applied a-c dielectric strength of mineral transformer oil as a function of its dissolved and suspended water content and the testing temperature

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting



degas mineral oil and other insulating liquids immediately after filter press or centrifuge treatment by passing the material through a vacuum chamber in the form of a thin film or spray. The assumption is usually made that such deaeration rapidly and effectively eliminates the dissolved water. This is not necessarily true. Mineral oil, even to the point where the dissolved air content is reduced to less than one per cent may still retain substantially large amounts of dissolved water. This was demonstrated in one form of commercial degassing equipment using mineral transformer oil containing 70 parts per million of water. After the degassing treatment, the oil still contained 46 parts per million of dissolved water.

A Practical Method for the Quantitative Estimation of Dissolved Water

A simple method for estimating the amount of water in solution in an insulating liquid involves the determination of its cloud point. Carefully carried out, the cloud point indicates that temperature below which the water in solution exceeds the saturation value of the liquid and separates with the formation of faint cloud. This water separation becomes pronounced and forms a turbid suspension in the liquid as the temperature is further lowered. This test procedure is limited to those materials free or substantially free from wax so that the formation of a cloud due to wax separation is avoided in the range of temperature of interest in dissolved-water determinations. Since, in general, the dielectric liquids in common use are of the naphthenic type of mineral oil or are synthetic benzenoid compounds free from wax separation on cooling, this

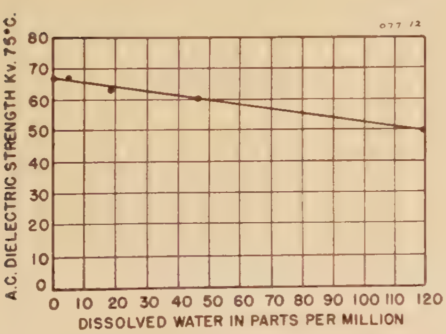


Figure 12. The effect of dissolved water on the rapidly applied a-c dielectric strength of mineral transformer oil tested at 75 degrees centigrade

All dielectric strength tests were taken with a 0.20-inch gap setting

limitation is not of serious significance.

The cloud-formation temperature relation to the liquid dissolved-water content is obtained from figure 1 for mineral transformer oil and from figure 2 for transformer Pyranol. The dissolved-water contents shown in these figures are those of the water-saturated condition for the corresponding temperatures. These temperatures are, therefore, the cloud-point values since further increase in water content or a further decrease in temperature results in the formation of a visible cloud.

The difficulty in the cloud-point test is that, except for the highest water contents, the test involves refrigeration with accompanying frost formation on the walls of the containing vessel and the necessity of protecting the liquid under test from water pick up due to frost formation on its surface. A suggested form

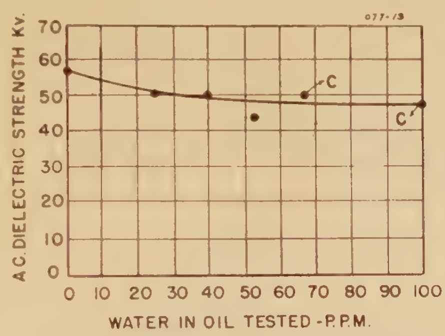


Figure 13. The rapidly applied a-c dielectric strength for mineral transformer oil tested at 25 degrees centigrade as a function of its dissolved and suspended water content

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

of test apparatus utilizes a clear vacuum bottle within which the liquid under test, contained in a clear-glass stoppered tube, is cooled at a standardized rate in accordance with principles of the method of test for the cloud and pour point of mineral oils, described under designation *D*97-34 of the American Society for Testing Materials.

The Effect of Dissolved Water on the A-C Dielectric Strength of Insulating Liquids

Repeated researches have indicated that the dangerously low dielectric strengths normally attributed to the presence of water in commercial insulating liquids are to be associated as well with the accidental presence of suspended

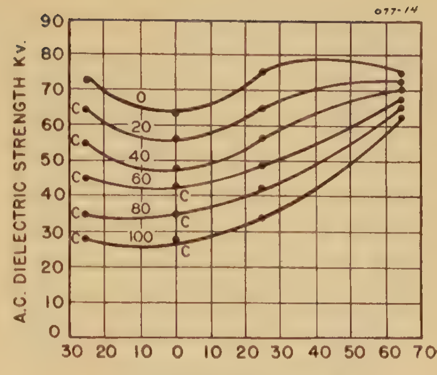


Figure 14. The effect of temperature and dissolved and suspended water in the a-c rapid applied dielectric strength of transformer Pyranol

Points marked C indicate that the oil contains suspended as well as dissolved water. The figures on the curves indicate the total water content of the liquid. All dielectric strength tests were taken with a 0.20-inch gap setting

solids such as dust particles, fibers, and the like.[1-4] It is undoubtedly true that mineral oil or other insulating liquid may contain appreciable amounts of dissolved water and, in the absence of suspended impurities, still retain what is commercially regarded as a good dielectric strength. This results in the fact, already indicated, that the dielectric-strength test as commercially applied does not give good protection against the insidious penetration of moisture through the liquid to the hygroscopic cellulosic insulation immersed therein. Irrespective of its effect on the dielectric properties of the liquid, unlimited penetration of moisture and its sorption by the cellulose must be avoided if satisfactory commercial operation of high-voltage apparatus is to be obtained.

Because of the unavoidable variation in water content during the handling and testing of an insulating liquid, it has been most convenient to determine the dielectric strength of the liquid for at least four water-content values covering the range of interest and from the smooth line (average) relation established, to select definite values of water content for comparison and further technical analysis. Thus, for example, the 75-degree-centigrade data of figure 11 are based on the smooth-line relation of figure 12 which describes the dielectric strength of mineral transformer oil at 75 degrees centigrade as a function of its dissolved-water content, the values indicated being experimentally determined. In general, the basic experimental data correlating the dielectric strength and the water content of the insulating

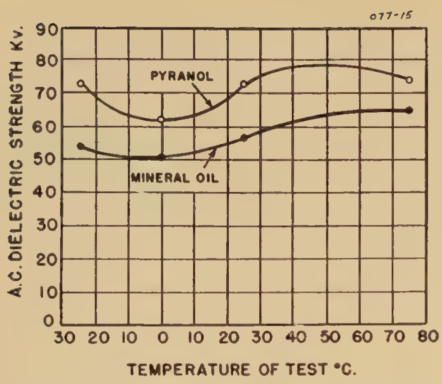


Figure 15. The comparative a-c rapidly applied dielectric strength of dry transformer Pyranol and dry mineral transformer oil

All dielectric strength tests were taken with a 0.20-inch gap setting

liquid are eliminated for reasons of brevity. The analyses which are shown are based on selected points taken from the smooth-line relation correlating the experimentally determined values.

The dielectric test results were obtained using brass electrodes meeting the requirements of the American Society for Testing Materials, designation *D*117-33. The gap distance used throughout was 0.20 inch. Temperatures recorded are the liquid temperature values at the time of test. In all instances, no dielectric-strength readings were made until the liquid had been at the testing temperature for several hours. The water-content values given include suspended as well as liquid dissolved moisture. The presence of suspended water is indicated.

Figure 17. The rapidly applied direct-voltage dielectric strength of mineral transformer oil as affected by tem perature and its dissolved and suspended water content

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

The rapidly applied dielectric strength has been determined in accordance with American Society for Testing Materials, designation *D*117-36, in which the voltage is evenly raised to breakdown at the rate of three kilovolts per second.

To define adequately the effect of dissolved and suspended water on the dielectric strength of an insulating liquid, it becomes evident at once that the temperature of test must be carefully specified. Practically speaking, a wide range of testing temperatures must be covered for liquid treated insulations are often used in high-voltage dielectric practice specifically because of the stability of their dielectric properties over a wide range of operating temperatures. In these tests, temperatures from −25 to

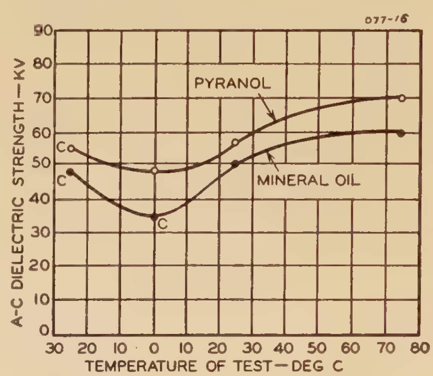


Figure 16. The comparative a-c rapidly applied dielectric strength of mineral transformer oil and transformer Pyranol, each containing 40 parts per million of dissolved water

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting

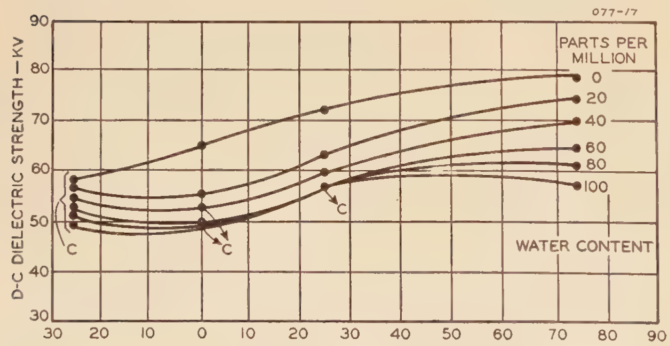
+75 degrees centigrade have been studied.

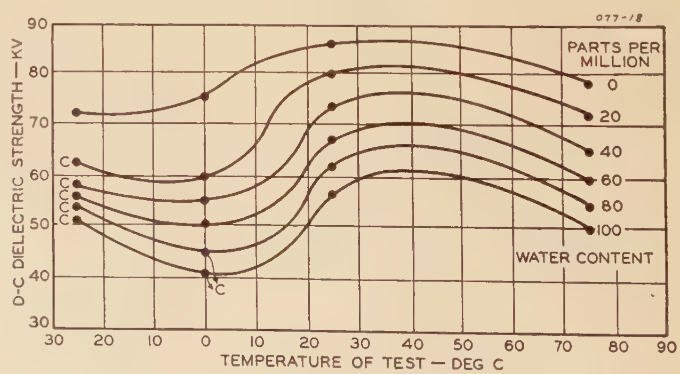
It has been pointed out in a previous publication[9] that the dielectric strength of mineral insulating oil as affected by temperature varies from oil to oil. With some oils, notably the viscous cable oils, the dielectric strength falls with temperature increase above room temperature. With mineral oils of the transformer type, the dielectric strength increases to a maximum with temperature increase above room temperature. The dielectric strength-temperature relation has been considered to reflect the solubility characteristics of dissolved air. In this study of the dielectric strength of mineral oil as affected by the dissolved and suspended water content, available data are limited to the behavior of air-saturated mineral transformer oil prepared from Gulf Coast crude and having a viscosity at 37.8 degrees centigrade of approximately 58 seconds Saybolt Universal. With such an oil, the effect of temperature increase on the dielectric strength is a function of its water content. The dielectric strength increases most rapidly with temperature increase from 25 to 75 degrees centigrade when the water content of the oil is held at low value. This is illustrated in the data of figure 11.

In any study of the effect of water on the dielectric strength of mineral oil, difficulty is at once experienced because of water separation as the temperature is lowered. This limits the study of the effect of dissolved water to a narrow range of water contents as the lower temperatures are investigated. Thus, as is shown in figure 12, even with a water content as large as 120 parts per million, clear solutions are obtained at 75 degrees centigrade and the decrease in dielectric strength with increased water content is easily demonstrated. At 25 degrees centigrade, however, the limit of water solubility as indicated in figure 1 for

Figure 18. The rapidly applied direct-voltage dielectric strength of transformer Pyranol as affected by temperature and its content of dissolved and suspended water

Points marked C indicate that the oil contains suspended as well as dissolved water. All dielectric strength tests were taken with a 0.20-inch gap setting





normally refined transformer oil is about 70 parts per million. The higher water contents of figure 11 are, therefore, cloudy suspensions. It is only with wet oil free from suspended water that a clear effect of dissolved water on the dielectric strength can be demonstrated. The dielectric strength for oil containing suspended water is independent of the water content within the limits explored (figure 13). For tests at lower temperatures similar results are obtained.

Synthetic, noninflammable transformer liquids of the Pyranol type have already been described as possessing a maximum dielectric strength at about 50 degrees centigrade.[10] As illustrated in figure 14 this is true for such liquids only when containing small amounts of dissolved moisture. With increased water content the dielectric strength rises continuously with the increasing temperature of test.

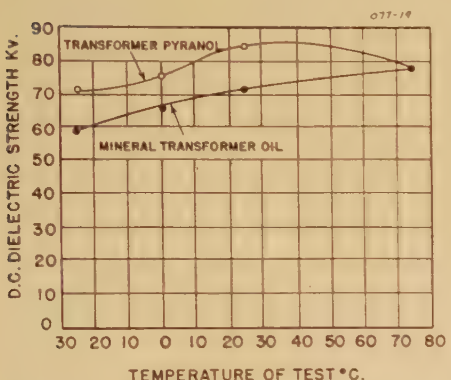


Figure 19. The comparative dielectric strength of dry mineral transformer oil and dry transformer Pyranol tested under direct-voltage application

All dielectric strength tests were taken with a 0.20-inch gap setting

Insulating liquids of the Pyranol type, as shown in figure 14, are characterized by a continually decreasing dielectric strength with increased water content. No abnormality in the relation is observed at the point of cloud formation, indicative of water separation from solution.

The Pyranol type of transformer insulating liquid in normally dry condition possesses a dielectric strength which is superior to that of mineral transformer oil. Figure 15 compares the dielectric strength of these two typical transformer liquids as affected by temperature when dry. Figure 16 compares the dielectric strengths of the two liquids each containing 40 parts per million of dissolved water.

The Effect of Dissolved Water on the D-C Dielectric Strength of Insulating Liquids

Under rapidly applied direct voltage, transformer insulating liquids behave in a manner similar to that already described for a-c breakdown. Figure 17 describes the d-c breakdown of mineral transformer oil as a function of temperature and water content. The general resemblance to the a-c breakdown values of figure 11 is marked. The effect of dissolved water is most clearly demonstrated in the 75-degree-centigrade tests. And again, as in the alternating-voltage breakdown, the formation of a cloud in the oil tends to obscure the effect of further water additions.

Figure 18 describes the d-c dielectric-strength characteristics of transformer Pyranol. As in the a-c breakdown data of figure 14, the effect of water content on the dielectric strength is marked.

Figures 19 and 20 compare the d-c breakdown characteristics of mineral transformer oil and transformer Pyranol. Figure 19 compares the materials in the dry condition. Figure 20 compares the materials each containing 40 parts per million of water. The dielectric strength of transformer Pyranol is generally higher than the dielectric strength of mineral transformer oil except at 75 degrees centigrade, at which temperature the two liquids appear of equivalent dielectric strength under direct-voltage tests.

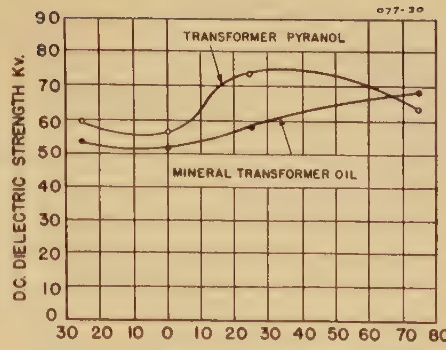


Figure 20. The comparative dielectric strength of mineral transformer oil and transformer Pyranol each containing 40 parts per million of dissolved and suspended water and each tested under rapidly applied direct-voltage application

All dielectric strength tests were taken with a 0.20-inch gap setting

The Time-Voltage Relation

The time-voltage characteristic applying to an insulating liquid is a property of difficult determination because of the sharp "knee" which is obtained in the relation at a relatively short time interval. That part of the time-voltage relation which parallels the time axis and which designates the voltage that can be

Figure 21. The time–alternating (effective) voltage relation for transformer Pyranol as affected by the dissolved and suspended water content

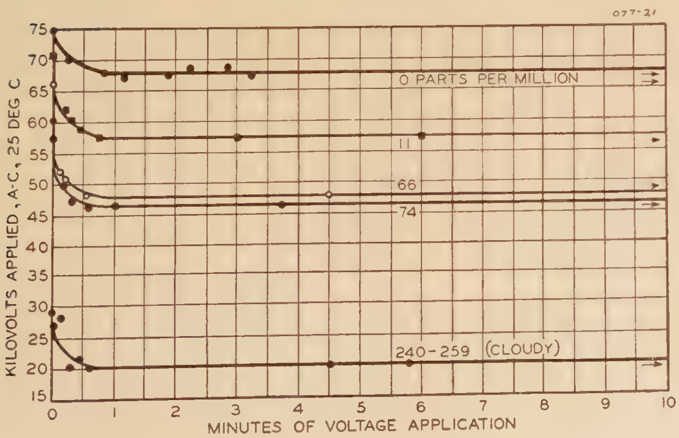
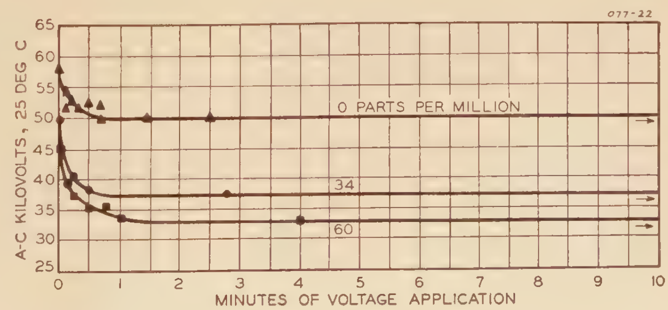


Figure 22. The time-alternating (effective) voltage relation for mineral transformer oil as affected by the dissolved water content

An arrow indicates that repeated applications of the voltage shown gave no dielectric breakdown within the time limitations of the test. All dielectric-strength tests were taken with a 0.20-inch gap setting



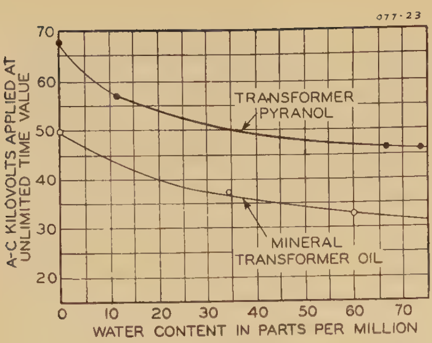


Figure 23. The "unlimited time" voltage value for transformer Pyranol and mineral transformer oil as affected by the water content of the liquid

All dielectric-strength tests were taken with a 0.20-inch gap setting

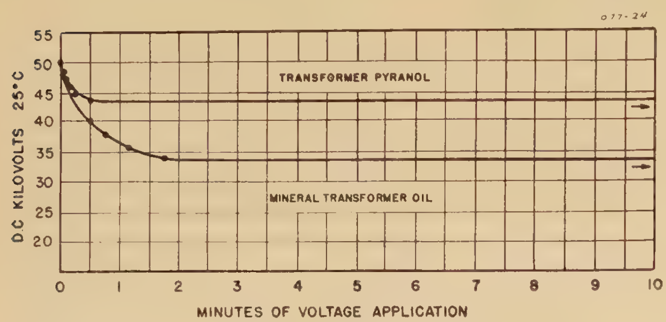


Figure 24. The time – direct-voltage relation for transformer Pyranol and mineral transformer oil each containing 60 parts per million of dissolved water

An arrow indicates that repeated applications of the voltage shown gave no dielectric breakdown within the time limitations of the test. All dielectric-strength tests were taken with a 0.20-inch gap setting

applied without fear of breakdown within the experimental time limit, is called the "unlimited time" value of voltage. In general, the maximum time allowed for breakdown in the work described has been limited to ten minutes. The electrodes used were duplicates of those employed in the rapidly applied test investigations and were spaced 0.20 inch apart. All tests were at 25 degrees centigrade. Both direct and alternating (effective) voltages have been studied.

Figures 21 and 22 describe the time-voltage (a-c) relation for transformer Pyranol and mineral transformer oil as affected by the dissolved and suspended water content. Figure 23 compares the effect of dissolved water on the "unlimited time" voltage values for mineral oil and Pyranol. The relations established are of marked similarity.

The direct-voltage–time relation for mineral transformer oil and transformer Pyranol bear strong resemblance to the alternating-voltage relation. This is indicated in figure 24 which illustrates the comparative behavior of these insulating liquids each containing 60 parts per million of dissolved water. Figure 25 shows the effect of dissolved water on the "unlimited time" direct voltage for transformer Pyranol over the range of water contents of practical interest.

The Relation of the Rapidly Applied to the "Unlimited Time" Breakdown Voltage

In the use of insulating liquids it is most convenient and reliable to gauge the dielectric strength by means of a carefully controlled rapidly applied alternating-voltage test. The determination of the "unlimited time" voltage is difficult and time consuming. For both transformer Pyranol and mineral transformer oil, the "unlimited time" voltage falls to approximately 70 per cent of the usual rapidly applied dielectric strength value as the water content of the liquid is increased at 25 degrees centigrade. The relation is illustrated in figure 26.

The D-C/A-C Ratio of Dielectric Strength

The relation between the rapidly applied d-c and the a-c (effective) dielectric strengths of mineral transformer oil and of transformer Pyranol has no fixed value. The ratio obtained for mineral transformer oil varies erratically between 0.89 and 1.58 as the temperature of test and the water content of the oil are changed. For transformer Pyranol, the range in d-c/a-c ratio value is between 0.89 and 1.37.

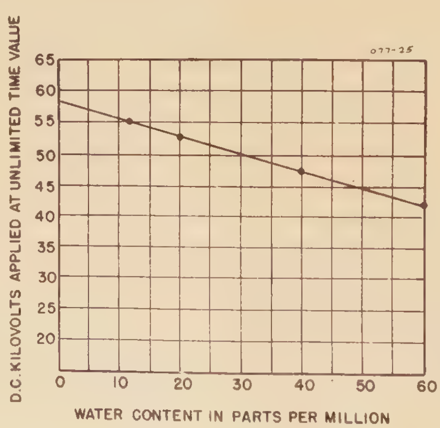


Figure 25. The "unlimited time" direct-voltage value of transformer Pyranol as affected by its dissolved water content

All dielectric strength tests were taken with a 0.20-inch gap setting

When the "unlimited time" voltage breakdown value is studied, a more consistent behavior of the d-c/a-c relation is observed. Figure 27 illustrates the ratio for transformer Pyranol using the "unlimited time" direct and alternating (effective) voltage values illustrated in figures 23 and 25. A ratio value linearly decreasing with the increased water content of the Pyranol is obtained. These tests were taken at 25 degrees centigrade.

Dielectric Loss

Mineral transformer oil has been selected to illustrate the effect of water solution on the dielectric loss. Several experimental setups were arranged which allowed the oil to be exposed at 25 degrees centigrade to air having relative humidity values of 24 per cent and 65 per cent. The apparatus used was similar to that already described under the paragraph entitled "The Hygroscopicity of Dielectric Liquids." Power factor and resistivity measurements were made at 25 degrees centigrade. The power-factor measurement was at 60 cycles under 3,000 volts. The resistivity was measured after the application of 500 volts direct current for one minute. The electrode gap setting in all cases was 0.10 inch.

Figure 28 illustrates the power-factor results obtained. From the dry-oil condition the power factor rises rapidly with increased water content to reach a maximum stable value at about 15 parts per million of dissolved water. Figure 29

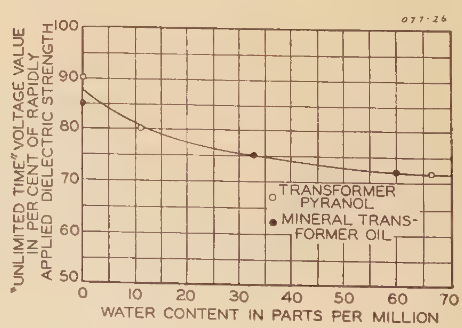


Figure 26. The effect of dissolved water on the "unlimited time" alternating-voltage value for transformer Pyranol and mineral transformer oil expressed in per cent of the corresponding rapidly applied dielectric strength

indicates a similar behavior for d-c resistivity measurements.

In considering the data of figures 28 and 29 it must be kept in mind that the oil tested was new oil uncontaminated by foreign materials or by oxidation products, the effect of which would necessarily be determined by their chemical and physical properties.

Cellulosic insulation is usually considered to be very susceptible to dielectric change caused by water. The presence of conducting salts and hygroscopic organic material serves to explain this marked susceptibility. Figure 30 describes the 30-degree-centigrade 60-cycle power-factor change in kraft-paper pads immersed in new mineral transformer oil and in new transformer Pyranol which are each exposed to humid air under conditions similar to those applying in the experimental setup of figures 28 and 29. The kraft-paper pads were originally well dried under a pressure about 0.3 millimeter of mercury at 100 degrees centigrade after which they were impregnated with the dry liquid. Although the data of figure 31 give no indication of the amount of moisture absorbed by the insulation, the test period covered several weeks and was sufficiently long for the insulation to reach an equilibrium with the water content of the surrounding liquid. Figure 30 leads to the conclusion that liquid-dissolved water does constitute a hazard to the successful maintenance of low-loss impregnated cellulose insulation. With new and unused insulating liquids, the 25-degree centigrade 60-cycle power factor of the impregnated cellulose insulation rises rapidly as the dissolved-water content of the impregnating liquid approaches and exceeds approximately 50 parts of dissolved water per million.

The effect on the power factor of liquid-immersed cellulosic insulation produced by moisture absorption becomes more pronounced as the temperature is raised above 50 degrees centigrade. This is illustrated in the data of figure 31. In this instance, carefully dried and impregnated kraft-paper insulating pads were immersed for 21 days at 70 degrees centigrade in transformer Pyranol, over the surface of which was maintained a layer of water about one-half inch deep. The sorption of water by the treated cellulose greatly increases the power factor at the higher testing temperatures.

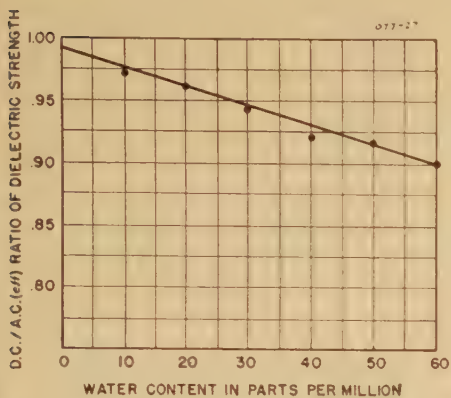


Figure 27. The 25-degree-centigrade "unlimited time" d-c/a-c (effective) voltage ratio of dielectric strength for transformer Pyranol as affected by its dissolved water content

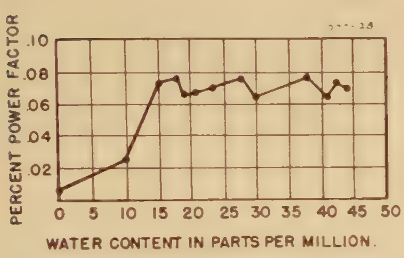


Figure 28. The effect of dissolved moisture on the 60-cycle power factor of mineral transformer oil measured at 25 degrees centigrade

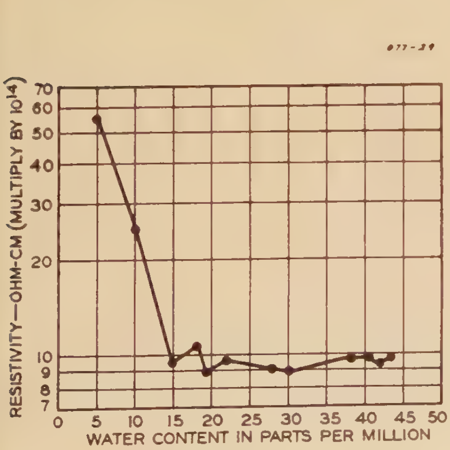
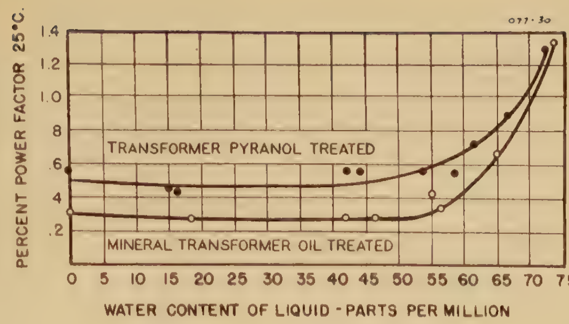


Figure 29. The effect of dissolved moisture on the d-c resistivity of mineral transformer oil measured at 25 degrees centigrade

Figure 30. The power-factor characteristics of vacuum-dried kraft paper insulation as affected by water absorption after impregnation with transformer Pyranol and with mineral transformer oil



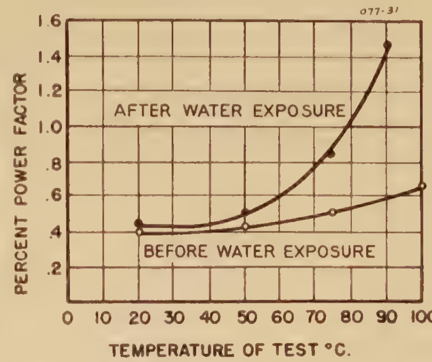


Figure 31. The effect of water absorption on the power factor temperature relation for transformer-Pyranol-impregnated kraft-paper insulation

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Lightning and Lightning Protection on Distribution Systems

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THE CONCEPTIONS of lightning and of lightning discharge currents through arresters have been altered and enlarged by recent studies. Until not long ago the most complete information available on the magnitude and wave shape of lightning surges on electric systems has been that obtained by the cathode-ray oscillograph investigations of lightning voltages, reported and discussed before the AIEE,[1] and elsewhere. Besides this there exists a large mass of data on the crest magnitudes but not the durations of currents in lightning strokes and arrester discharges. Based on the data available two conclusions have been generally held: one, that in a small percentage of discharges, the currents may be high, perhaps 65,000 amperes or more; and two, that the total duration of the discharge might be of the order of 100 microseconds, but not much more. Lightning-arrester design was based principally upon these conclusions. Arresters available during the past six or eight years have in general been able to discharge high currents of the durations cited without damage. In the field, the over-all experience with such arresters has been good. Throughout the country the average failure rate of Autovalve distribution arresters manufactured during that period has been less than a quarter of one per cent per year. However, in rural locations in some parts of the country failure rates of three to four per cent have occurred. This is considered excessive. The variation in failure rates led to the suspicion, several years ago, that there are characteristics in arrester discharge currents that had not been taken into account and which are themselves influenced by such factors as lightning exposure, stroke characteristics, ground resistance, and system characteristics. It is true that to some extent the significance of the data may be obscured by failures from abnormal system voltages and by the performance of obsolete arresters, but these factors were not sufficiently weighty to explain the observations.

The purpose of this paper is to discuss the present state of our knowledge of this matter resulting from the observations and investigations of the authors and their colleagues. We do not propose to provide a complete answer at this time to the questions raised because insufficient field data exist. The authors hope that this paper will stimulate others to give the subject study. It is expected that a considerable volume of informative data will be available after another season's research with "fulchronographs," the recently developed surge wave recorders.

Paper 40-60, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted October 28, 1939; made available for preprinting December 20, 1939; released for final publication March 11, 1940.

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1. For all numbered references, see list at end of paper.

Inspection of Arresters

A systematic inspection of Autovalve arresters removed from service was undertaken several years ago by our associates. Arresters that had failed in service as well as arresters which had not were examined. A surge discharge of high crest or of appreciable duration leaves a distinctive mark on the series-gap electrodes. This serves as an indication of crest current and duration if not obscured by power current. Crest currents above 3,000 amperes of short duration (less than 100 microseconds) leave marks like splashes. A low current of a few hundred to a thousand amperes of long duration (1,000 or more microseconds) produces a small pit with definite evidence of burning. Currents of high amplitude and long duration cause local melting of metal. A calibration of the appearance of the surge tracks as related to current magnitude and duration has been made. Typical results are shown in figure 1*a*.

Comparisons of electrodes from arresters that had seen service were made with the laboratory calibrations. Figure 1*b* shows representative field electrodes. These are especially significant because all but number 5 came from arresters installed on a line struck by lightning while it was unenergized. There is thus no question of masking by power current even in the cases where the arresters failed. Typical currents of high crest and short duration appear in 1, 2, and 3. The crests are of the order of 50,000 amperes and the durations approximately 50 microseconds. Number 2 has additional marks indicating other surges of lower crests. The elements of these arresters were not injured. Records 4 and 5 are typical low-current long-duration markings. They indicate currents of the order of a few hundred to 1,000 amperes crest lasting several thousand microseconds; moreover they indicate that several such discharges took place. These arresters failed. Other data of the same nature have given similar information. The following conclusions were reached:

1. Arrester discharge currents of low magnitude and long duration occur.
2. Such discharges are more likely to cause arrester failure than very high currents of short duration.
3. As far as arresters in service are concerned, either type of discharge may occur independent of the other.
4. It is important that field data be collected on the magnitude and wave shape of the discharge currents that prevail and which arresters must meet for a reasonable life expectancy under severe conditions; and to correlate these data with the factors that appear to influence the nature of the discharge currents in service.

These conclusions definitely pointed to a revision of our thinking about lightning-arrester discharge currents. Other observed circumstances strengthen this opinion.

Statistical Data on Arrester Performance

Figure 2 gives an indication of the variation of arrester failure rates over a number of systems. This curve was plotted from statistical data presented by L. G. Smith before the AIEE in 1937.[2] One-half of the companies reporting arrester failure data on more than 1,000 transformers experienced failure rates of less than 0.3 arrester per 100 transformers, but a few reported failure rates of two or more. The paper shows a ratio of four to one between rural and urban systems. Other significant data were presented by McEachron and McMorris in 1938.[3] Many crest measurements without duration of arrester dis-

Figure 1a. Surge marks on lightning-arrester gap electrodes obtained in laboratory tests

1—57,000 amperes crest; 12 microseconds to crest; 26 microseconds total duration

2—725 amperes crest; 10 microseconds to crest; more than 4,000 microseconds total duration

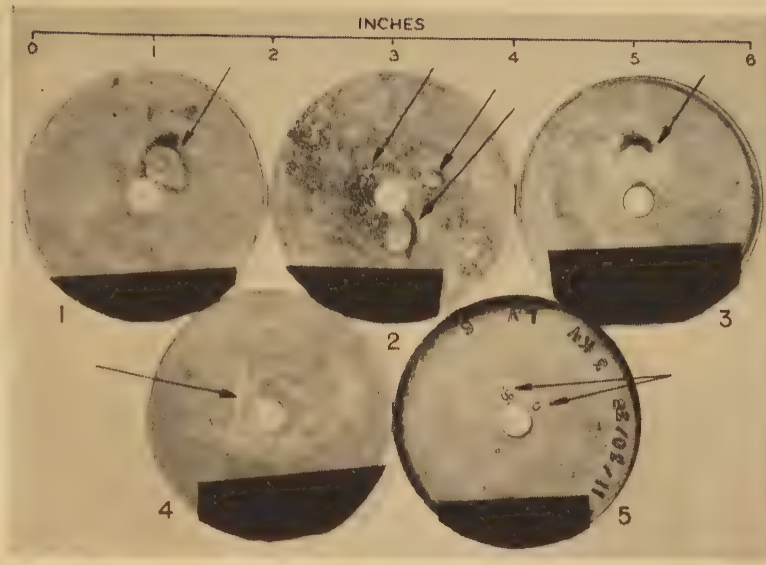


Figure 1b. Surge marks left by lightning discharges through arresters in the field

1—High short current
2—Several discharges of high short currents
3—High short current
4—Several discharges of moderate current. Several hundred amperes, but of long duration, probably more than 4,000 microseconds
5—Several discharges of moderate long current; 500 and 1,000 amperes, several thousand microseconds

All plates but number 5 from arresters on unenergized line

Arresters of 1, 2, and 3 were electrically undamaged. Arresters of 4 and 5 failed

charge currents are reported there and the occurrence of arrester failures is apparently not related to their magnitudes or to their relative frequency of occurrence on different systems in different parts of the country. Figure 7 of that paper is of considerable interest. It compares the frequency of occurrence of crest currents of various magnitudes on two different systems. Although the Detroit data indicate a greater prevalence of high currents, the observed failures of arresters are higher in Georgia. Low currents occur more often in Georgia than in Detroit. McEachron and McMorris report that 68 per cent of the observed arrester failures took place in Georgia although only 34 per cent of all the records were obtained there.

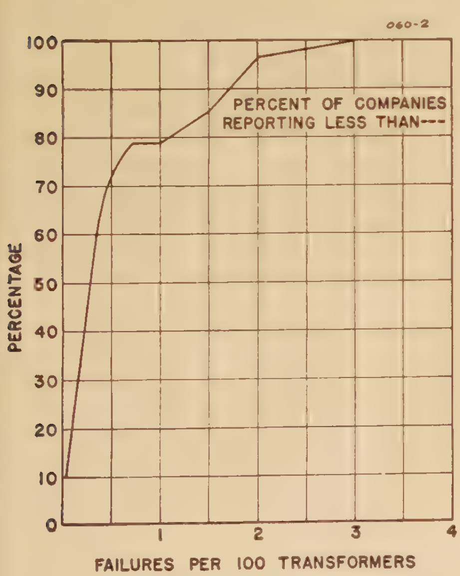


Figure 2. Statistical data on the relation between number of companies reporting arrester failure rates on more than 1,000 transformers

Number of companies considered, 33

Data culled from reference 2. Includes all protective circuits, average of 1934, 1935, and 1936 reported data

Stroke Characteristics

Photographic studies of strokes by several investigators, for instance Schonland and Collens, and Walter, indicated the probability that strokes may not only be multiple but also may involve moderate or low-current components of considerable duration. Stekolnikov and Valeev[4] in 1936 made records of lightning currents to a captive balloon. A rotating klydonograph used by them indicated that the duration of current flow lay between 2,600 and 10,000 microseconds. McEachron's work on the Empire State Building[5] also gave evidence of this phenomenon. Last summer, Wagner and Beck[6] obtained a complete record of the current in a direct stroke to the Cathedral of Learning of the University of Pittsburgh which definitely showed both high short and low long components. The oscillograph studies on lines had not indicated that this occurred on systems, but the authors suspect that because of the sensitivity limitations of the cathode-ray oscillograph the low long component may have been present but not revealed.

There is definite evidence that the long low components will frequently, if not always, appear in strokes to tall conductors. It is probable that the characteristics of strokes to lines are different from those to high objects but there is sufficient evidence to be convincing that long-duration components appear also to some extent on lines when struck by lightning.

New Recording Instrument

The available measurements of stroke currents cannot be translated into arrester duty until a significant volume of wave-shape data on strokes and arrester discharges in the field has been collected. This had not been done for lack of a recording device sufficiently low in cost to be installed in considerable numbers. The invention of the fulchronograph by Wagner and McCann described by them in a contemporary paper has made the needed device available.

It is evident that crest currents only without the important factor of duration did not give a complete understanding of arrester duty. The work has been begun. In co-operation with a number of utilities, many fulchronographs were installed during the summer of 1939, and already a considerable number of records has been obtained.

The fulchronograms of discharges through arresters in service are not yet of the desired technical significance. No records have been obtained accompanied by arrester failure. Records falling toward the expected extremes of high current or of long duration have not been secured. They do indicate, however, that arresters sometimes are called

upon to handle, and do so successfully, considerable blocks of current (figure 3) appreciably in excess of the existing AIEE standard test. The paucity of heavy surges is not unexpected, inasmuch as experience with fixed link records as well as with arresters indicates that harmless currents are much more frequent. Some typical fulchronograms are shown in figure 3. These are all records of discharge through individual phase legs of arresters. Numerous records have been made of discharges of less than 1,000 amperes and short duration.

The observations and tests discussed in the foregoing show that the occurrence of long-tailed moderate-current surges accounts for the abnormally high failure rates experienced in certain rural regions on the basis that in these regions arresters must discharge such surges more frequently. The ability of the De-ion protector such as is used in the *CSP* transformer, to handle currents of long duration probably accounts to a large extent for its low failure rate in service.

Effect of System Characteristics

Low-current discharges through arresters are fairly common. This is demonstrated, for instance, by published substation and distribution transformers are in parallel with the arresters and provide possible paths to ground for part of the current in long surges. A study was made of the current drainage characteristics of these shunt paths. The following discussion covers a typical example to illustrate the effects of system characteris-

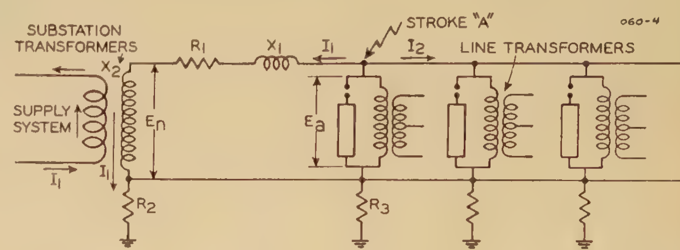


Figure 4. Surge-current drainage paths in parallel with distribution arresters

For I_1 see figure 5, and I_2 see figure 6

E_a—Arrester counter voltage

E_n—Alternating voltage to neutral

To use figure 5, calculate a-c short-circuit current at arrester nearest stroke with sufficient accuracy by using $R=(R_1+R_2)$ and $X=(X_1+X_2)$ (60 cycles), where X_1 is taken as 0.75 ohm per mile and X_2 is the substation transformer plus supply-system leakage reactance. Variation of R_3 through a 10–50 ohm range does not change I_1 appreciably

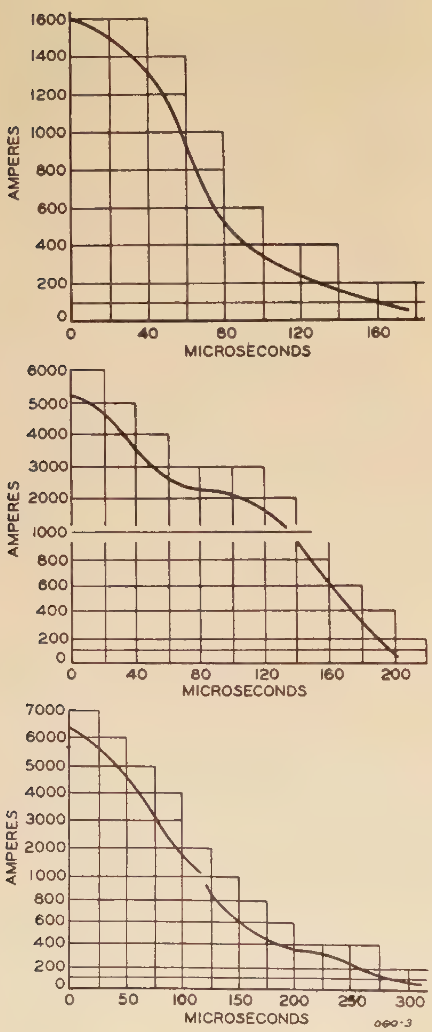


Figure 3. Typical records of discharge currents through single-phase legs of lightning arresters in service, obtained with the fulchronograph

data.[3] Figure 3 of the reference indicates that among 100 rural arrester installations, discharges of the following crest magnitudes (no data on duration) may be expected.

Amperes exceeding:	500	1,000	2,000	5,000	10,000	15,000
Discharges per year:	40	33	20	7	3	2

If the comparatively numerous low-current discharges through arresters were all or to a major extent of the long duration which might be expected from the observed stroke characteristics, laboratory tests on all types of distribution arresters would lead us to expect much higher arrester failure rates than those experienced and published.[2] Since many strokes evidently have these long low-current components there must be drainage effects present in many instances that relieve arresters installed on systems of some of this current.

Line flashovers from steep-front strokes to the line at points remote from arresters will by-pass a large proportion of the surge current. The effects of soil resistivity both on the degree of current drainage and perhaps on the character of the stroke itself may partly explain the difference in failure rates. In general, it has been found that where soil resistivity is high, arrester failures are more frequent. In addition to this, however, variations in arrester failure rates between locations resembling each other in insulation levels and soil resistivity point to another factor.

On grounded-neutral systems, both

tics. In figure 4 is shown a long single phase circuit with distribution transformers and arresters, fed by a substation transformer. A stroke to the first arrester will discharge initially through it and possibly also through adjacent arresters depending on the surge front. With a steep-front stroke close to, or a slow-front stroke remote from an arrester, line flashover will not occur and all of the stroke current is carried by the arrester or arresters discharging first. The stroke current flowing into the system is assumed, for purposes of calculation, to have a low-current component of 1,000 amperes of such length that it may be considered a direct current. For durations of 1,000 microseconds or more this is entirely justified. This current, discharging through the arrester, produces a voltage at the arrester terminals, which in turn is impressed on the system. The magnitude of the voltage is the counter voltage of the arrester corresponding to the discharge current. Laboratory tests (figure 11) show that the counter voltage of the Autovalve arrester under these conditions is, in round numbers, 6,000 volts per 3,000 volts of arrester rating. This is not the crest arrester voltage on the volt-ampere curve but a voltage on the descending part of the curve, near the so-called "cut-off". The initial voltage while carrying high current can be neglected because of its short duration. For purposes of calculation, then, it is assumed that 6,000 volts per 3,000 volts of arrester rating are applied continuously to the resistance and inductance of the

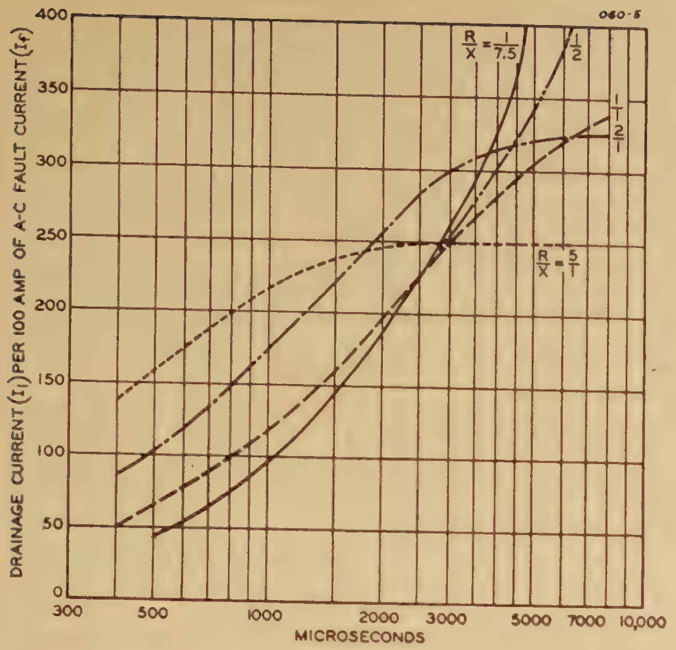


Figure 5. Surge current drained from arrester through line conductors and substation transformers

(Current I_1, in figure 4)

These curves based on $E_a = 2.5E_n$ which is an arrester counter voltage of 6,000 on a 2,400-volt circuit or 18,000 on a 7,200-volt circuit

Since the range of a-c fault current (I_f) on a feeder is generally known, the drainage current I_1, which is proportional to it, was plotted accordingly. To use the curves, calculate I_f from R, X (60 cycles) and E_n of the figure 4 system, and use the appropriate R/X ratio curve in plotting the leakage current I_1 versus time

circuits through the supply and distribution transformers. These were found to have entirely different characteristics.

The substation transformer has connected to its receiving winding the supply system of low impedance. The current I_1 of figure 4 to the substation ground will build up through the inductance of the line, the leakage inductance of the transformer and the supply source, that is, in the ordinary a-c short-circuit path. In figure 5, I_1 is plotted per 100 amperes of feeder fault current for several values of the ratio R/X_{60}. These curves apply to higher voltage as well as 2,400-volts-to-neutral systems because the arrester counter voltage is proportional to the arrester rating. With small conductors, ($R/X = 2/1$ to $5/1$, the drainage current to the substation ground is soon limited by line resistance.

The current I_2 flows in the other drainage path through the distribution transformers to ground. Since the secondary load impedances are high this current must build up through the magnetizing path. To determine the growth of current I_2, a $1^1/_2$-kva distribution transformer was subjected to suddenly applied continuous potential and the current measured by an oscillograph. Figure 6 shows the increase of current in terms of full load rms current of the transformers with 6,000 volts continuous applied to 2,400-volt windings or 18,000 volts applied to 7,200-volt windings. Until the iron begins to saturate at about 1,000 microseconds the current flow is imperceptible but after this it increases rapidly. The 1,000 microseconds applies under the conditions of test with no flux in the iron at the instant of application of the voltage. If the lightning voltage is applied at the instant the flux is zero, the curve applies as it stands. If the voltage appears when the flux is at its peak in the same direction, the time is much less, possibly zero. If it appears when the flux is at its opposite peak, the time will be much greater up to about twice 1,000 microseconds. To consider the most severe conditions it is assumed that 2,000 microseconds elapse before I_2 starts to flow.

The total current, I_1 plus I_2, that is drained away from arresters on typical 2,400- and 7,200-volt distribution systems is shown in figure 7. Up to 2,000 microseconds the drainage may be through the substation transformers only. Curves 1 and 2 show that for strokes near substations (3,000 to 1,000 kva, three phase) current is drained away rapidly. This also applies to a less extent on short heavy city feeders as shown in curve 3. Suburban and heavy rural circuits are represented in curves 4 and 5. Curve 6 applies to a typical rural circuit, while curve 7 represents extremely light rural distribution.

From curves 1, 2, and 3 of figure 7, it is apparent that for 1,000-ampere surges of long duration, the arrester discharge current will be reduced to zero in from 130 to 700 microseconds in city locations but for typical suburban distribution as indicated by curve 5, the arrester current will persist for some 2,500 microseconds where it is abruptly limited by drainage of current through the line transformers. The shape of curve 5 shows also that the suburban arresters are subjected to a higher average current.

On light rural systems the situation is the most unfavorable. The small size of the supply transformer and the high resistance of the line prevent much drainage to the substation. Fifteen miles of number 8 copper has a resistance of 53 ohms, which would pass only 340 amperes at the 18,000-volt counter voltage of a 9,000-volt arrester usual on a 7,200 volt system. Furthermore, the light branch fuses on these circuits are blown easily. With blown fuses, only the limited capacity of the distribution transformers can be depended upon for drainage, so conditions on grounded-neutral rural lines may be even worse than shown by curve 7.

In this connection it is suggested that the drainage of appreciable amounts of surge current through transformers may explain the occasional blowing of light transformer fuses with arresters connected on the line side of the fuses and no discernible evidence of flashover on the transformers.

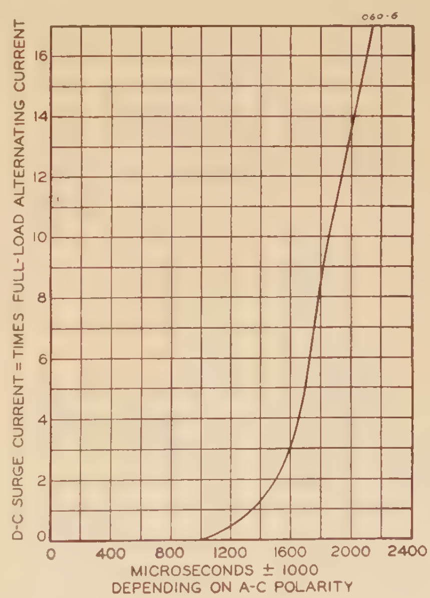


Figure 6. Surge current drained from arrester through magnetizing path of line transformers

(Current I_2 in figure 4)

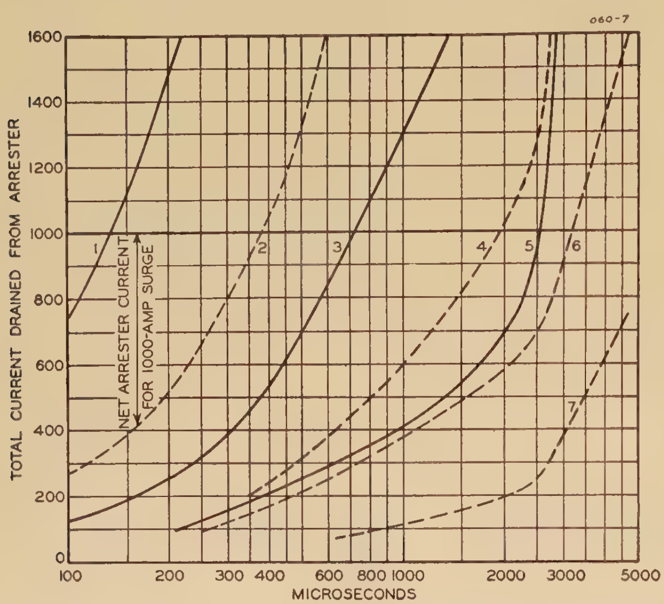
Based on applying direct voltage of 2.5 times rms alternating voltage rating of transformer, that is, $E_a = 2.5E_n$ (figure 4) which is an arrester counter voltage of 6,000 on a 2,400-volt circuit or 18,000 on a 7,200-volt circuit. Load impedance is so high that secondary was considered open-circuited

While there are other factors already enumerated to be considered, experience has shown that the failure rate of arresters increases progressively with conditions represented by the ascending curve numbers of figure 7. We would also expect from this analysis that arrester failure rates on free-neutral systems should be higher than on grounded-neutral systems. It is further significant that the locations of abnormally high distribution-arrester failure rates mentioned early in the paper fall in the region of curves 5 to 7.

The fulchronograms reproduced in figure 3 were recorded on arrester phase legs installed at a transformer whose neutral is grounded. The circuit characteristics are such that for the assumptions made in figure 7, the current drained from the arresters should be in the region of curve 2. This curve predicts an arrester discharge duration of not much more than 300 microseconds. The fulchronograms of figure 3 appear to corroborate the calculations. Apparently, all of the evidence available to date supports the conclusions.

Application of Conclusions to Arrester Construction

The observations and investigations discussed in the foregoing explain to a large extent, at least, the variations in arrester failure rates on distribution systems as well as the probable causes of high failure rates. Thus far, the data presented are relative because not enough information on the actual wave shapes of discharge currents through arresters are at hand. Nevertheless, the conclusions appeared of sufficient importance two years ago to warrant an active investigation of arresters' ability to handle long discharges with the object of increasing this ability, without sacrifice of any of the high current capacity or protective characteristics. After all, the significance of the conclusions lies in whether they can be translated into a new and better arrester. Experience with an arrester tailored to these new concepts has been favorable. It gives additional corroboration and clarification to the aspects already discussed. The extremely low failure rate experienced with these arresters indicates that an increase in the ability to take long surges increases the immunity to failures in service.



Below 2,000 microseconds, all current flows to the substation. (Current I_1 calculated from figure 5). Above 2,000 microseconds, the line transformers begin to saturate and I_2, calculated from figure 6, increases sharply. Actually, this may occur at any time from zero to 2,000 microseconds, depending on the instantaneous magnitude and polarity of the a-c magnetic flux in the iron at the time of the stroke. Refer to table below

Figure 7. Total current drained from arresters through transformers of typical distribution systems

	Curve Number: 1	2	3	4	5	6	7
Voltage to neutral	2,400	7,200 or 2,400	2,400	7,200	2,400	7,200	7,200
Substation transformer kva per phase	1,000	1,000 or 333	1,000	333	333	333	50
Size line conductor	None	None None	No. 00	No. 4	No. 2	No. 4	No. 8
Miles from stroke to substation	0	0 0	2	5	5	20	15
Line transformer kva assumed all at one point	0	.0 0	0	300	200	100	75

Field Experience

On a system which, in the past, has had a distribution-arrester failure rate at the top of figure 2, a direct comparison between two arrester types is available. One type is the new one under discussion. The other is the superseded Autovalve arrester, with equal ability to handle high currents of short duration, but with less ability to take the long low ones. In a total of 950 of the new arresters in service during the 1939 lightning season, there were no failures, against a failure rate of several per cent on the others during the same period.

For lack of measured data, the ultimate demands in long current-carrying capacity are not yet known. Nor is it known exactly what can be done economically to meet what those ultimate demands may turn out to be, or to what degree the new arrester meets them. It will not eliminate failures entirely. However, on the basis of laboratory tests and field experience, it is expected that even in the unfavorable locations the failure rate will be low.

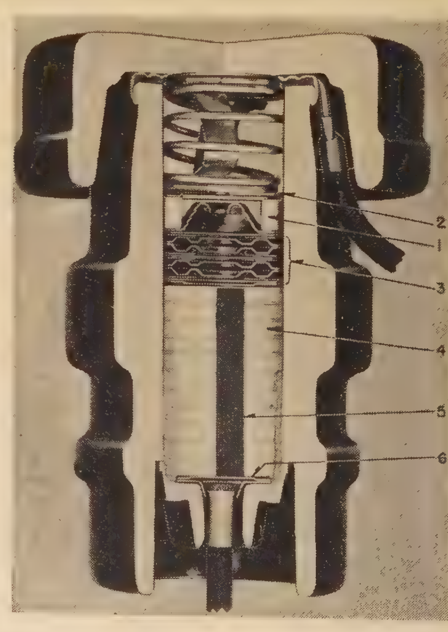


Figure 8. 3,000-volt Autovalve distribution lightning arrester, cutaway section

1—Porcelain-insulated main gap
2—Gap electrode with preionizing tips
3—Quenching gaps
4—Autovalve element with white insulating coating
5—Insulating coating cut away from element for purpose of illustration
6—Terminal plate, ground lead, and ferrule soldered together

The first field-trial installations were made in 1939, to gather operating experience before the design was adopted for production. Several thousand units were placed in locations where previous failure rates have been higher than normal. Two hundred fifty were in service throughout the 1938 season. No failures occurred. By the end of 1938 some 1,200 were installed. Before the spring of 1939, the number was 4,000, and this had more than doubled by the fall. There has been a total of four failures; one of these was definitely caused by system voltage. The other three occurred late last summer on the same system near the ends of lines. Inspection of these three arresters indicated that they were caused by lightning. Thus the lightning failure rate has been 0.043 per cent compared to the quarter of a per cent mentioned in the first paragraph of this paper.

Construction

The principal factor in determining the ability of the arrester to discharge long surges is the valve element. Its failure can be thermal, or it can be caused by a function involving current density, voltage gradient, and duration of discharge. In long-duration discharges the latter cause is more weighty than the thermal. The recognition of this was important for it pointed out a means of making a distribution arrester of large current-carrying capacity without increasing its cross section. If the length of the block is doubled and its composition adjusted so that the total voltage across it during discharge is the same as in the case of the shorter element, the voltage gradient is halved. This reduction in voltage gradient effects a large increase in the ability of the elements to handle discharges of long duration. The use of such an element in the arrester is the major reason for its large discharge ability. Other detail features permit the utilization of the valve material to its full capabilities; such as a newly developed insulating coating and a particular design of terminal for making contact with the valve blocks.

The series gap structure consists of a

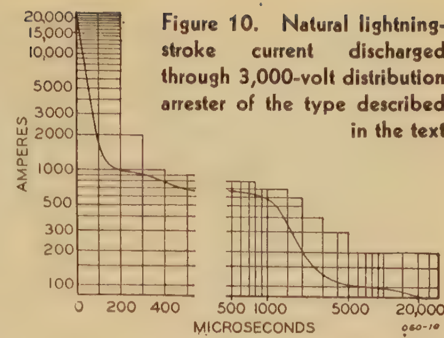
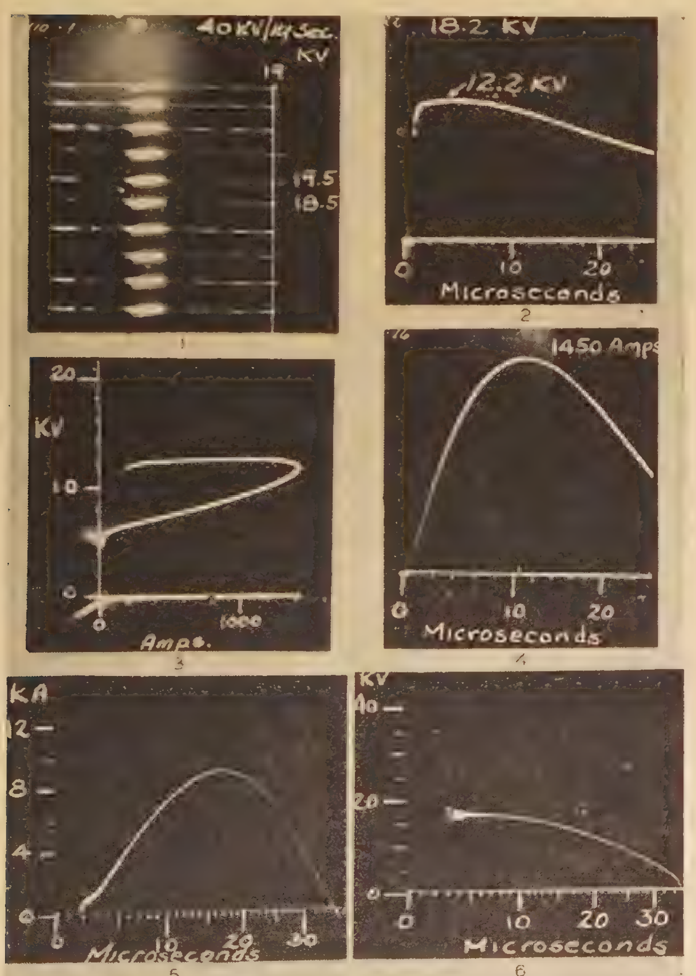


Figure 10. Natural lightning-stroke current discharged through 3,000-volt distribution arrester of the type described in the text

The current was derived from a lightning stroke to the Cathedral of Learning Building in Pittsburgh.[6] The current was recorded by a fulchronograph. After this test, the arrester was checked in the laboratory and found unchanged in its characteristics

quenching gap, item 3 in figure 8 with high 60-cycle interrupting ability, and a porcelain-insulated line or main gap, items 1 and 2. The high interrupting ability of the gap provides a margin of safety against failures from high system voltage. The use of mica spacers in the quenching gap and of a special main gap electrode, item 1, provides preionization of the gap spaces and produces low and consistent impulse breakdowns, as illustrated in oscillogram 1 of figure 9, which also shows the discharge characteristics of the arrester on the basis of AIEE standards. The favorable impulse ratios obtained with this construction permit the incorporation of a high 60-cycle breakdown, thereby providing additional margins against dynamic voltage failures.

During the development of this arrester, many tests were made with moderate discharge currents of long duration as well as with high currents. A novel test was completed when a lightning stroke occurred to a measuring station on the roof of Pittsburgh University's Cathedral of Learning.[6] The entire stroke current was discharged through one of the new distribution arresters, connected in the stroke-current circuit, and was recorded by a fulchronograph. This current is shown in figure 10. Subsequent laboratory tests on the arrester showed that its condition had not been altered by the discharge. As far as the authors are aware, this is the first time that an arrester has deliberately been put in the path of a stroke and successfully discharged the full stroke current. The performance of the arrester on laboratory surges of long duration and of high magnitude are shown in figures 11 and 12. Oscillogram 1 of figure 11 is typical in shape of the surge used in routine testing of valve elements to insure the use in complete arresters of only



1—Successive impulse breakdown tests on a 3,000-volt arrester. Rate of rise of test voltage 40 kv per microsecond. No time deflection used in oscillograph. Voltage deflection from left to right. Vertical line marked 19 is crest of 60-cycle breakdown

2—Volt-time curve of same arrester on AIEE test wave shown in 4

3—Volt - ampere characteristic of same arrester, test current as in 4

4—Ampere - time characteristic of test current used in 2 and 3

5—Ampere - time characteristic of 9,000-ampere test current used in 6

6—Volt-time characteristic of 3,000-volt arrester on test wave shown in 5

Figure 9. Impulse characteristics of new distribution arrester

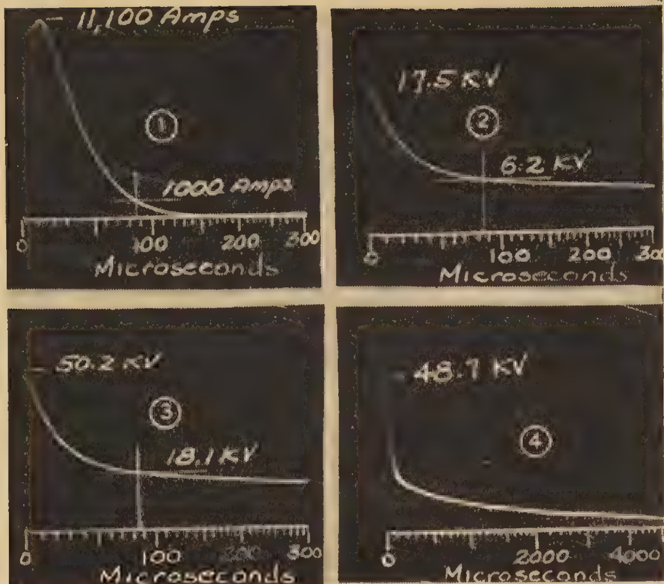


Figure 11. Performance of distribution arrester on long surge

1—Discharge current through arresters used in recording 2, 3, and 4

2—Volt-time characteristic of 3,000-volt arrester with discharge current of 1

3—Volt-time characteristic of 9,000-volt arrester with discharge current of 1

The points on 2 and 3 marked 6.2 and 18.1 kv are the voltages corresponding to 1,000 amperes in 1. These are the basis for assuming 6,000 volts per 3,000 volts of arrester rating in the derivation of figures 5, 6, and 7

4—Volt-time characteristic of 9,000-volt arrester with long time scale. This oscillogram shows that there is voltage across the arrester even after 4,000 microseconds, indicating that the arrester is still discharging current. In 1, the current is not discernible after 150 microseconds because of the current scale used

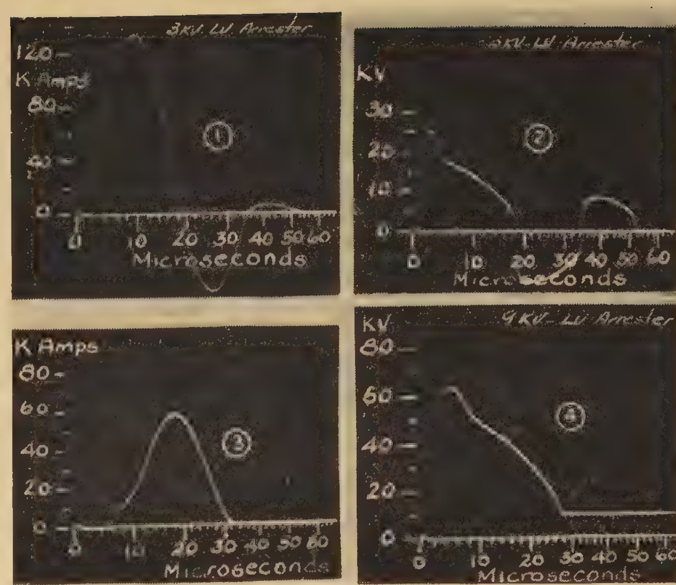


Figure 12. Performance of distribution arrester on high discharge currents

1—High current discharge through 3,000-volt arrester

2—Volt-time characteristic of 3,000-volt arrester with discharge current of 1

3—High current discharged through 9,000-volt arrester

4—Volt-time characteristic of 9,000-volt arrester with discharge current of 3

The difference in current between the 3,000- and 9,000-volt arresters is caused by the difference in the counter voltage of the two. Both were tested in the same surge-generator circuit. The voltage across the 9,000-volt arrester for the current in 1 is three times the voltage recorded in 2

elements able to handle long-tailed discharges.

This test surge used on distribution arrester elements resembles the recorded discharge currents of figure 3, but is longer in duration. The routine test is made while the arresters are excited at rated 60-cycle voltage. The adoption of such a test procedure is perhaps as important a development as the new construction used in the arrester.

Other characteristics have been given due weight in the development, such as safeguards against lockouts by failed arrester on low-capacity systems, and the avoiding of interference with radio reception. Discussion of these is without the scope of this paper. However, the authors wish to say a few words on the matter of radio interference.

Radio interference has not been a problem in arresters constructed during the past eight years. Laboratory tests with standardized radio-noise-measuring technique are factors in the development of any arrester. However, a considerable amount of attention is being directed to this subject as well as to so-called ionization currents, synonymous with radio-noise currents. For this reason it is to be desired that the committees concerned with this question adopt standards of permissible microvolt levels to which the industry will subscribe and adhere. In this connection, it may be of interest that in the arrester discussed in this paper the occurrence of low ionization currents at a voltage below actual arrester breakdown but above its rating is promoted and utilized to achieve low and consistent impulse breakdown.

Summary

The text of this paper concerns itself almost entirely with one aspect of the problem of distribution circuit protection, that of arrester discharge currents and the lightning-arrester failure rate. There are other phases of the problem such as the important one of protection to equipment At this time, however, it is believed that the most important problem is the matter of eliminating as far as possible the failures of protective devices even under severe operating conditions. It is hoped that the work described in the paper has contributed to the solution of this problem, and there is some reassuring evidence that it has, contained for instance in the field records of an arrester designed to meet conditions disclosed by the studies already outlined.

Much research has been done on lightning, particularly on the lightning stroke. This will no doubt result, in time to come, in important new concepts of protection. However, the present practical aspect of the protective problem is concerned with the discharges through lightning protective devices in service, and not with the currents in direct strokes. For this reason, the authors attach the greatest importance to an accumulation without delay of a volume of statistical data on the magnitude and wave shape of such discharge currents, to permit a definite evaluation of the present means of protection, the economic possibilities,

Table I. Summary of Arrester Characteristics

Arrester rating, volts	3,000	6,000	9,000
60-cycle breakdown, volts rms	14,000	24,000	35,000
Impulse breakdown, volts crest*	20,000	40,000	58,000
Discharge voltage at			
1,500 amperes†	12,500	25,000	37,500
5,000 amperes†	15,000	30,000	45,000
10,000 amperes†	17,500	35,000	52,500
20,000 amperes†	18,500	37,000	55,500

The above values are average.
* On front of 50 to 100-kv-per-microsecond test wave.
† 10 by 20-microsecond current wave.

Watt-Hour-Meter Performance With Power Rectifiers

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Synopsis: This paper gives the results of tests made principally to determine the effect of 6- and 12-phase mercury-arc power-rectifier loads on the performance of typical polyphase watt-hour meters. Schematic diagrams of the connections used and oscillograms of the rectifier voltage and current waves are included. The results indicate that the effect to be expected will be well within one per cent.

IT IS well known that mercury-arc power rectifiers introduce harmonics in the alternating supply current and voltage waves [1-4] and this has been thought to affect adversely the accuracy of watt-hour meters on circuits including rectifiers. The subject has been investigated previously, notably by Dannatt,[5] but interest in it is still current. It was considered highly desirable, therefore, to make more comprehensive tests, utilizing the best obtainable equipment and methods, to determine the actual effect of commercial types of 6- and 12-phase rectifiers under approximate conditions of service on the performance of typical polyphase watt-hour meters used with instrument transformers. At the suggestion of W. C. Wagner, a var-hour meter (reactive-volt-ampere or rva-hour meter) was included; also included was a portable power-factor meter.

In these tests, the performance of five watt-hour meters was determined at various loads, first with one of the two rectifiers and second with a sine-wave supply under corresponding three-phase conditions. The differences between the meter accuracies thus obtained are a measure of the effect of the rectifier and are referred to the sine-wave results as a standard. A similar procedure was followed for the var-hour and power-factor meters.

The paper first summarizes the test results, then describes briefly the apparatus tested and the related theories of performance, outlines the procedure followed, and discusses the data obtained. The ratings of the apparatus are given in table I and part of it is shown in figures 1 and 2. Schematic diagrams of the test connections are shown in figures 3 and 4 and the measurement equipment in figure 5.

Summary of Results

The results of the watt-hour meter tests are given in table II, which shows that the maximum change in watt-hour meter performance due to the effect of the rectifiers is less than 0.5 per cent. Table II gives the detailed effects or the differences between the accuracies obtained with the rectifiers and with a sine-wave supply at corresponding points for the five watt-hour meters tested. The accuracies so obtained in the 6-phase rectifier tests are included in table III and are plotted in figure 8; the 12-phase rectifier results are plotted in figure 9. In general, the results obtained with the two rectifiers and the two types of meters are similar in magnitude. In both tests, the rectifier effect tends to decrease the meter speed at light load. At higher rectifier outputs, the 6-phase effect tends to increase the meter speed, whereas the 12-phase effect becomes negligible.

Three representative oscillograms taken during the 6-phase rectifier tests are shown in figure 6 and the analyses are given in table IV, part 1. This table includes an analysis of the oscillogram shown in figure 7 for a 12-phase rectifier. The maximum harmonics occur with the 6-phase rectifier, but the harmonic power is small, as indicated in table V.

The results of the var-hour meter tests are given in table III and are plotted in figure 10. The maximum change shown in var-hour meter performance due to the 6-phase rectifier is less than one per cent. The rectifier effect tends to increase the meter speed at light load and to decrease it at higher outputs.

Table III also gives the results of the power-factor meter tests, together with the instrument readings from the watt-hour meter tests. Three values of power

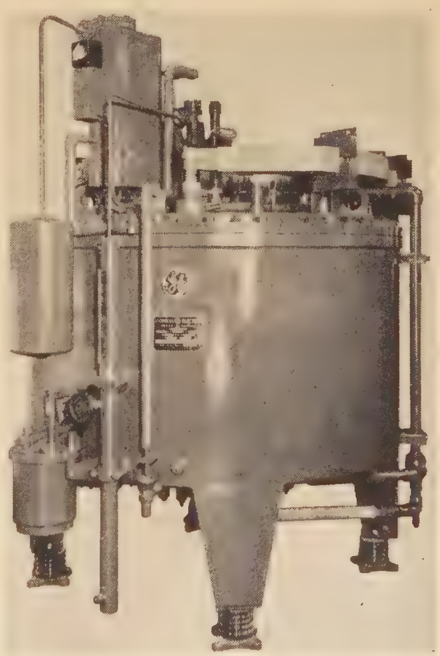

Figure 1. Six-phase mercury-arc power-rectifier tank rated type RHW, 1,675 kw, 515 volts

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The authors desire to acknowledge the assistance of G. F. Gardner and of many other of their associates in carrying out the tests.

1. For all numbered references, see list at end of paper.

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and the prediction of the failure rates of protective devices under the conditions of service that are encountered.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

factor are given for each pair of tests as follows:

(*a*). Power-factor-meter reading

(*b*). Power factor calculated from the formula

$$\text{power factor} = \text{polyphase watts/voltamperes} = P/\sqrt{3}EI \quad (1)$$

(*c*). Vector power factor calculated from the formula

$$\text{vector power factor} = \text{polyphase watts} \div \sqrt{\text{watts}^2+\text{vars}^2} = P/\sqrt{P^2+Q^2} \quad (2)$$

Formulas 1 and 2 are based on American Standards Association definitions; they are here restricted to balanced circuits, as is (*a*).

With the sine-wave supply, the power-factor-meter readings (*a*) in table III agree fairly well with the two corresponding calculated values of power factor (*b*) and (*c*) in each case. With the 6-phase rectifier, the expected good agreement is shown between the power-factor-meter readings (*a*) and the corresponding calculated values of vector power factor (*c*). Good agreement is not expected between the power-factor-meter readings (*a*) and the corresponding calculated values of power factor (*b*) based upon the ASA definition; the maximum difference shown is 0.030 (=0.976–0.946) or about three per cent: this difference is a function of the harmonics present.

The rectifier effect represented by the difference between (*a*) and (*b*) may be expressed by the ratio (*a*)/(*b*), which here has a maximum value of 1.032 (=0.976/0.946), or as (*c*)/(*b*). The lowest power-factor values are those determined from equation 1.

Conclusions

The rectifier current and voltage waves obtained in the tests are believed to be fairly representative of those encountered in practice.

The maximum effect of such rectifier waves on the performance of watt-hour meters should be well within one per cent; this conclusion is based upon all of our experience to date. The corresponding limit for a var-hour meter should be two per cent.

The effect of a 12-phase rectifier on the power factor should be less than the three per cent (ratio 1.032) obtained with the 6-phase rectifier. For both 6- and 12-phase rectifiers, the ratio (*a*)/(*b*) should aproximate the ratio

$$\frac{\text{effective value of balanced line currents}}{\text{effective value of fundamental component}} \quad (3)$$

when the harmonics in the balanced voltage waves are small as in these tests. The maximum value obtainable for ratio (3) with a 6-phase rectifier is 1.045 and it is 1.010 with a 12-phase rectifier. Thus, the maximum differences to be expected between the readings of a power-factor meter and the power factor calculated from equation 1 with such rectifiers should be within five per cent and two per cent, respectively.

The significance of the terms "power factor" and "reactive power" when harmonics exist in the system current and voltage waves is a matter of opinion[6–8].

The results upon which table II is based are believed to be correct within ±0.2 per cent.

A—Type *DS*-19

B—Type *V*-3-*A*

Figure 2. Polyphase watt-hour meters rated 120 volts, 2.5 amperes, three-phase, three-wire, 60 cycles

Mercury-Arc Power Rectifiers

A 6-phase rectifier tank is shown in figure 1. The auxiliary equipment includes a main power-supply transformer in one or three units connected to convert 3-phase power to 6- or 12-phase power, an interphase transformer, vacuum pumps, and suitable control devices.[3,4]

The function of a complete rectifier is to convert a-c power to d-c power, usually for electric traction or electrochemical purposes. In so doing, it draws nonsinusoidal currents from a system generating sinusoidal voltages. These currents, in flowing through the system impedances, create nonsinusoidal voltage drops, which combine with the line voltages to give nonsinusoidal voltages at the rectifier terminals. The nonsinusoidal currents are composed of the fundamental and various harmonics, the orders of which depend on the number of rectifier phases; the magnitudes are an inverse function of the orders.[1] The nonsinusoidal voltage drops have the same harmonics, but the harmonic magnitudes depend on the magnitudes of the system impedances as well as on the magnitudes of the currents.[2] The formulas for the order and magnitude of the harmonic currents are as follows:

$$\text{Order of harmonic } n = mp' \pm 1 \quad (4)$$

$$\text{Per cent harmonic } h = 100/(mp' \pm 1) = 100/n \quad (5)$$

where

m = any number from 1 to infinity

p' = number of rectifier transformer secondary phases

The maximum obtainable percentage values of the harmonic currents due to the rectifier occur at light load and these estimated values are shown for 6- and 12-phase rectifiers in table IV, part 2*A*, up to the 25th harmonic, the fundamental being taken as 100 per cent; the orders of the harmonics also are shown. It should be noted that the magnitude of the harmonics decreases as their order increases and that harmonics common to both rectifiers, such as the 11th and 13th, have identical respective values. In practice, these magnitudes will ordinarily be somewhat less than those listed. Also, due to various causes, small amounts of the 5th, 7th, 17th, and 19th harmonics will be present with 12-phase rectifiers. For a given rectifier, the percentage harmonics will decrease with load, but the actual harmonic currents will increase; in other words, the harmonic components do not increase as fast as the fundamental.

Different rectifiers may be compared as to the relative amounts of harmonics expected in the input currents at full load by means of the load coefficient. The formula is:

$$\text{Rectifier load coefficient} = IX/E_0 \quad (6)$$

Table I. Ratings of Apparatus Tested

	Units	Type	Cycles	Phases	Kva	Kw	Volts	Amp
Mercury-arc power rectifiers								
6-phase rectifier	1	*RHW*	60	6		1,675	515	3,250
			60	6		2,233*	515	4,333*
Main transformer	3	*H*	60	1	1,130		13,200	
Interphase transformer	1	*H*	180/360					
12-phase rectifier	1	*RDW*	60	12		2,000	625	3,200
Main transformer	1	*HTD*	60	3	3,370		14,200	
Interphase transformer	1	*H*	180/360					
Meters and instrument								
Two-element watt-hour meter	3	*DS*-19	60	3	0.52	($K=0.6$)	120	2.5
	2	*V*-3-*A*, *BE*1	60	3	0.52	($K=0.6$)	120	2.5
Two-element var-hour meter	1	*DS*-19	60	3	0.52	($K=0.6$)	120	2.5
Double autotransformer	1	*MC*-1	60	3			115/115	
Power-factor meter	1	*P*-3		3	0.87		100	5

* Extended rectifier rating.

where

I = d-c load current per group of main-transformer secondary windings

X = reactance of circuit in which commutation takes place

E_0 = crest voltage to neutral of main-transformer secondary winding

The effect of IX/E_0 at full load in reducing the light-load harmonic percentages is shown in table IV, part 2*B* for assumed values of 0.04 and 0.08: the latter is considered representative of many rectifiers. For example, take the 13th harmonic. For both rectifiers, "39" corresponds to 0.08, which means that 39 per cent of the light-load harmonic of 7.7 per cent will be present; this gives 3 per cent for the 13th harmonic: the corresponding value for $IX/E_0 = 0.04$ is 5 per cent. The percentage of harmonic present tends to decrease as the order of harmonic increases; the decrease for the 5th harmonic is small: conversely, the percentage increases with decreasing values of IX/E_0.

The term X in IX/E_0 represents the sum of the system reactance and that of the rectifier transformer; the system reactance (and the losses therein) ordinarily is less than ten per cent of the total. The harmonic power to be measured, therefore, is but a small part of that due to the rectifier, which in turn is but a small part of the fundamental power. The harmonic and fundamental powers have opposite signs. If the system voltage itself contains some of the harmonics expected from the rectifier, however, the net harmonic power may be positive instead of negative.

Ratio (3) is a function of the harmonics in the input currents. The maximum value of 1.045 for this ratio with a 6-phase rectifier is obtained when all possible harmonics attain the maximum possible magnitude; table IV, part 2, includes those up to the 25th. The maximum value of 1.01 is similarly obtained with a 12-phase rectifier.

Watt-Hour Meters

One of the type *DS*-19 watt-hour meters tested is shown in figure 2*A* and one of the type *V*-3-*A* meters in figure 2*B*. Both types have the same rating and are designed for three-phase three-wire service, usually with instrument transformers. The switchboard-type *DS*-19 meter employs two electromagnetic structures and two disks mounted on a common

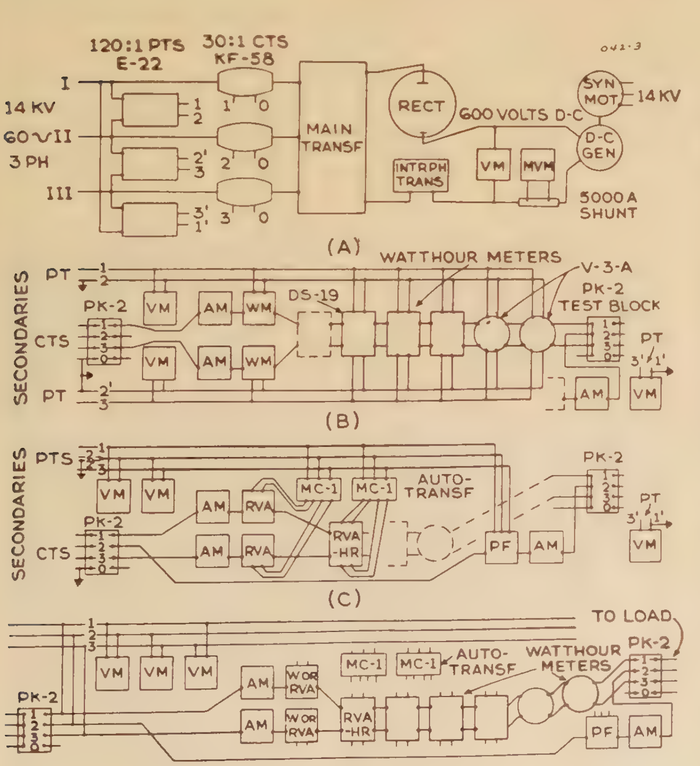


Figure 3. Schematic measurement circuits for rectifier tests

A—Rectifier input and output

B—Rectifier supply for watt-hour meter tests

C—Rectifier supply for var (rva)-hour meter tests

D—Sine-wave supply for check tests

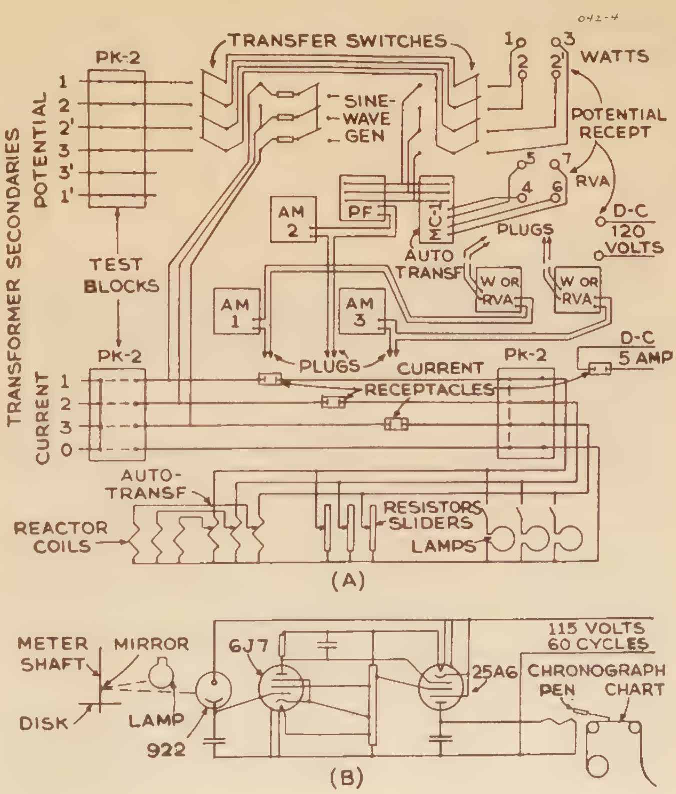


Figure 4. Schematic instrument and auxiliary circuits

A—Potential and current supply—load control for check tests

B—Meter-disk revolution counter

Table II. Effect of Rectifiers on Watt-Hour-Meter Performance (Difference Between Rectifier and Sine-Wave Results)

Test Number	Rectifier: Output (Per Cent)	Rectifier: Load Coefficient IX/E_0	Input (P-3 Instruments) (Average of Three): Volts	Input (P-3 Instruments) (Average of Three): Amp	Input: Three-Phase Watts	Power Factor ($P/\sqrt{3}EI$)	Watt-Hour Meters; Per Cent Difference (Referred to Sine Wave): DS-19: 1	DS-19: 2	DS-19: 3	V-3-A: 4	V-3-A: 5
6-phase rectifier											
1	21.5	0.015	116.9	0.571	109.9	0.950	−0.1	−0.1	0	−0.1	−0.3
2	57.5	0.044	116.6	1.515	289.3	0.946	−0.1	−0.1	−0.1	−0.1	−0.3
3	86.9	0.066	117.1	2.279	436.6	0.944	+0.1	+0.1	+0.1	+0.1	−0.1
4	113.6	0.086	117.9	2.973	570.3	0.939		+0.1	+0.2	+0.1	−0.1
5	135.8	0.105	118.3	3.568	684.6	0.936	+0.2	+0.2	+0.2	+0.1	−0.1
6	154.2	0.120	118.1	4.078	777.8	0.933	+0.1	+0.2	+0.2	+0.1	−0.1
12-phase rectifier											
1	18.2	0.008	118.2	0.551	108.4	0.961	−0.2	−0.3	−0.4		−0.3
2	35.4	0.015	118.0	1.061	210.0	0.969	+0.1	+0.1	+0.1	+0.1	+0.1
3	62.6	0.027	118.0	1.850	367.8	0.973	0	0	0	0	0
4	83.3	0.036	117.3	2.482	491.5	0.974	0	0	−0.1	0	0
5	92.8	0.041	116.2	2.812	550.8	0.973	0	0	−0.1	0	−0.1

shaft. The bottom-connected type *V*-3-*A* meter employs a more recent construction, in which both electromagnets act on a common disk. Interference is rendered negligible by the use of magnetic shields and by laminating the disk, thereby segregating the fluxes and eddy currents.

Tests made here and elsewhere have shown that such induction-type meters tend to become slower as the applied frequency increases. Thus 60-cycle meters would be slow at 300 cycles; in other words, they would not register fifth harmonic power correctly and larger errors would be obtained with higher harmonic powers. In some cases, correlation has been shown[5,10,11] between the performance of a meter on distorted waves and its performance on the component harmonic frequencies.

Var-Hour Meter

The var(rva)-hour meter tested is a type *DS*-19 watt-hour meter with its two potential circuits supplied from a type *MC*-1 double autotransformer instead of directly from the two line-to-line system voltages. By means of suitable taps, the autotransformer lags each voltage 90 degrees in order to measure the reactive component of the energy.[9] A similar unit supplied two indicating watt(var) meters to measure the reactive power.

The active power in a balanced three-phase three-wire sine-wave circuit may be determined from the formula

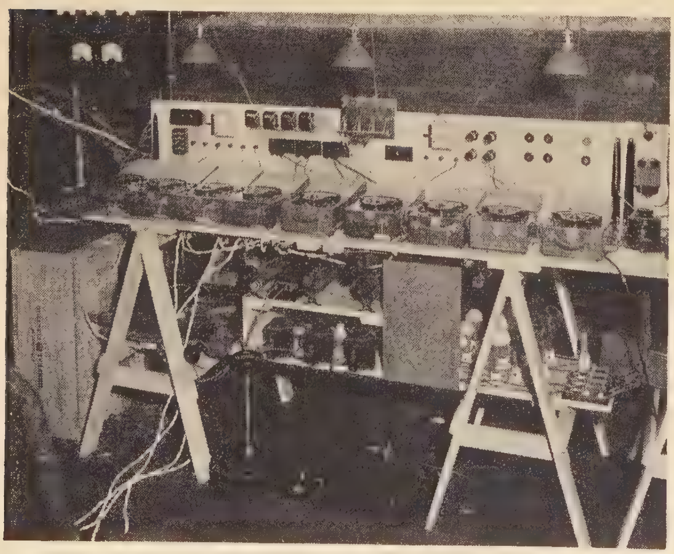
$$\text{watts} = \text{line-to-line volts} \times \text{line amperes} \times \sqrt{3} \times \cos\theta = \sqrt{3}EI \cos\theta \quad (7)$$

where θ is the angle between the voltage to neutral and the line current. Similarly, the reactive power may be obtained from the formula

$$\text{vars} = \sqrt{3}EI \sin\theta \quad (8)$$

The former quantity may be measured by two wattmeters and the latter by two varmeters. The varmeters will function correctly also on circuits with unbalanced currents, but neither formula can be used as the line currents are unequal and θ is meaningless. The wattmeters will function correctly on any sort of three-wire circuit.

Equations 7 and 8 may be used for balanced circuits and "θ" may be taken to represent the "angle" between voltage and current when the current waves contain harmonics. However, each wattmeter then measures the product of its sine-wave voltage and the in-phase component of its current. Since the fundamental component is smaller than the total current, the correct power factor (by ASA definition) or cos "θ" obtained from equation 1 will be smaller and "θ" will be larger than if no harmonics were present. Therefore, sin "θ" and the calculated reactive power will be larger than the measured value, the difference



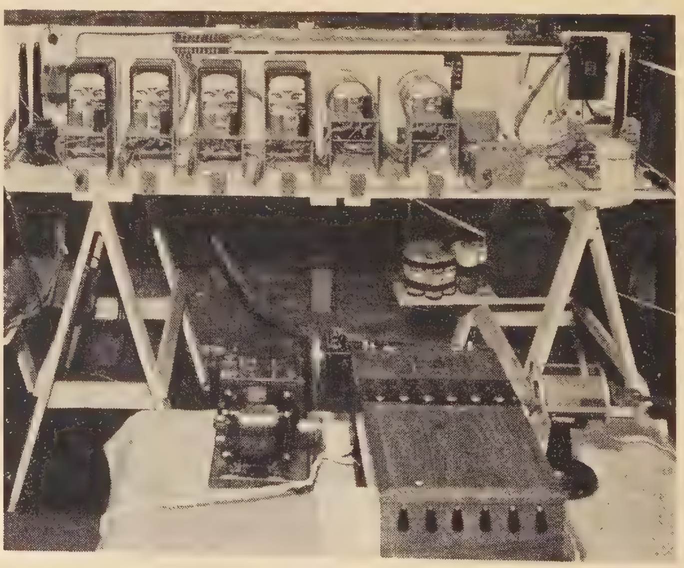


Figure 5. Measurement equipment—indicating instruments and transfer panel, sine-wave loading devices and control—watt-hour meters, revolution counters, chronograph and oscillograph

being a function of ratio (3). Also the vector power factor or cos θ determined from equation 2 will be the same as that read on a power-factor meter and both will be greater than the value determined from equation 1 in the ratio (3).

The foregoing discussion will still be pertinent when the harmonics in the voltage waves are small. However, it has been shown[8] that correct measurement of reactive power is impossible when the harmonics in both the voltage and current waves are appreciable.

Power-Factor Meter

The type *P*-3 portable power-factor meter tested is designed for use on balanced three-phase three-wire circuits only and has one current coil, which is connected in series with the "common" line. There are two potential coils mounted at an angle on the shaft and the two potential circuits are connected from the other two lines to the "common" line. Essentially, two wattmeters are combined in one instrument without a control spring, so the deflection depends on the ratio of the two torques, which is a function of the power-factor angle θ. The scale is marked in power factor and the range is from 0.5 lag through 1.0 to 0.5 lead.

Test Connections and Procedure

The tests described herein were made in connection with the standard acceptance tests on the two rectifiers. The measurement equipment is shown in figure 5. The meter accuracies were determined first with one of the two rectifiers and second with the sine-wave supply. The correct three-phase watt (or var) values were obtained in each test from the readings of two single-phase watt (or var) meters, which were checked with the d-c supply by means of potentiometers. The correct power factor was calculated from equation 1, which requires the readings of eight different instruments.

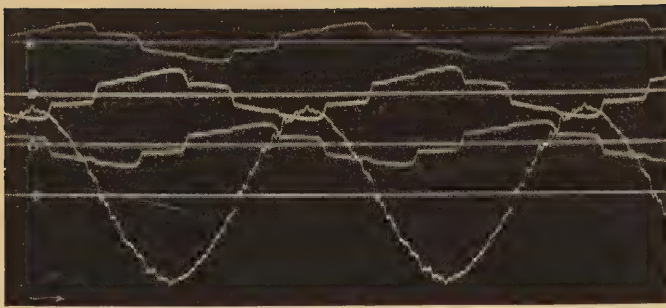
Connections

The connections used are shown schematically in figures 3 and 4. Figure 3*A* shows the general arrangement of the rectifier input and output circuits and indicates the feed-back scheme adopted for acceptance tests on large rectifiers. The small numbers on the instrument transformer secondary leads correspond to similar numbers in figure 3*B*, which shows the arrangement for the watt-hour meter tests. The arrangement for the

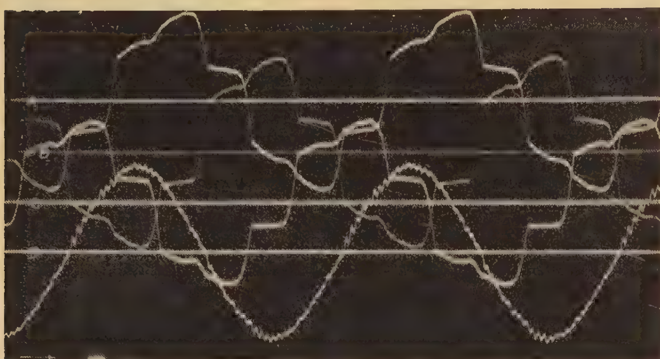
Table III. Watt-Hour, Var-Hour, and Power-Factor Meters (Six-Phase Rectifier and Sine-Wave Results)

	P-3 Instruments					(a)	(b)	(c)		Watt-Hour Meters Per-Cent Accuracy					Var-Hour Meter Per Cent	
	(Average of Three)		Three-Phase							DS-19			V-3-A			
Test Number	Volts	Amperes	Volt-Amperes	Watts	Vars	Power-Factor Meter	Power-Factor $\left(\frac{P}{\sqrt{3}EI}\right)$	Vector Power-Factor $\left(\frac{P}{\sqrt{P^2+Q^2}}\right)$	Reactive Factor $(Q/\sqrt{3}EI)$	1	2	3	4	5	Accuracy	Diff.*
Input to 6-phase rectifier (through instrument transformers)																
1	116.9	0.571	115.7	109.9			0.950			100.1	99.9	100.1	100.0	99.8		
1*a*	117.0	0.592	119.9		28.52	0.977		0.968	0.238						98.1	+0.2
2	116.6	1.515	305.9	289.3			0.946			100.0	100.0	99.9	99.9	99.8		
2*a*	116.4	1.508	304.0		67.16	0.976		0.974	0.221						99.4	−0.1
3	117.1	2.279	462.3	436.6			0.944			100.1	100.1	100.1	100.1	99.9		
3*a*	117.0	2.266	459.4		106.5	0.971		0.972	0.232						99.7	−0.4
4	117.9	2.973	607.1	570.3			0.939			[illegible]	100.1	100.2	100.1	99.9		
4*a*	117.8	2.956	603.2		152.4	0.965		0.966	0.253						99.5	−0.4
5	118.3	3.568	731.4	684.6			0.936			100.2	100.2	100.2	100.0	99.9		
5*a*	118.1	3.474	710.6		186.7	0.962		0.965	0.263						99.3	−0.6
6	118.1	4.078	833.9	777.8			0.933			100.1	100.1	100.2	99.9	99.8		
6*a*	119.3	4.083	843.6		233.4	0.959		0.958	0.277						99.1	−0.8
Supply from sine-wave alternator (direct) Check Number																
1	116.6	0.585	118.2	114.0			0.964			100.2	100.0	100.1	100.1	100.1		
1*a*	116.8	0.585	118.3		33.61	0.972		0.959	0.284						97.9	
2	116.1	1.501	302.0	293.0			0.970			100.1	100.1	100.0	100.0	100.1		
2*a*	116.2	1.503	302.4		69.27	0.975		0.973	0.229						99.5	
3	117.6	2.197	447.6	433.7			0.969			100.0	100.0	100.0	100.0	100.0		
3*a*	119.0	2.215	456.5		108.9	0.972		0.970	0.239						100.1	
4	118.4	2.942	603.3	579.7			0.961			100.0	100.0	100.0	100.0	100.0		
4*a*	118.4	2.946	604.1		160.5	0.963		0.964	0.266						99.9	
5	117.5	3.564	725.4	694.3			0.957			100.0	100.0	100.0	99.9	100.0		
5*a*	117.7	3.567	727.1		198.0	0.963		0.962	0.272						99.9	
6	117.4	4.038	820.9	782.7			0.953			100.0	99.9	100.0	99.8	99.9		
6*a*	117.7	4.037	823.2		232.4	0.959		0.959	0.282						99.9	

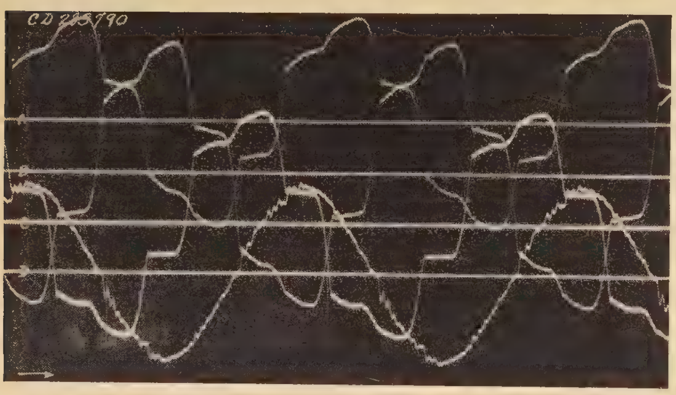
* Difference between rectifier and sine-wave results; this is the rectifier effect: the watt-hour-meter differences are in table II. Power-factor columns (*a*), (*b*), and (*c*) are explained in the text of the paper.



A—At 22 per cent output



B—At 114 per cent output



C—At 156 per cent output

Figure 6. Oscillograms showing wave shapes of voltage and current, six-phase mercury-arc power rectifier rated type RHW, 1,675 kw, 515 volts

Curve *A*—Secondary current in line 1

Curve *B*—Secondary current in line 2

Curve *C*—Secondary current in line 3

Curve *D*—Secondary voltage across lines 1–2

var-hour and power-factor meter tests is shown in figure 3*C*. In *B* and *C*, meters not under test are indicated by dotted lines. Figure 3*D* indicates the arrangement for the sine-wave supply, which constituted the standard test condition for all meters.

The necessary connection changes were made by means of single- and double-throw potential switches, type *PK*-2 potential and current test blocks, and potential and current receptacles and plugs. These are shown in figure 4*A*. In the rectifier tests, the magnitude of the currents through the various instruments and the six meters (not shown) was determined by the load on the rectifier. In the sine-wave checks, the corresponding currents and power factors were obtained by means of the variable noninductive and inductive loads shown at the bottom of figure 4*A*. The line-to-line voltages were set at approximately the desired values by means of remote generator field control.

The method of automatically counting the revolutions of the six meter disks is shown in figure 4*B*. A small mirror is fixed on each meter shaft to reflect the light from a small lamp to photoelectric tube 922. This tube operates the coil of a suitable pen through a tube network. Each pen records each revolution of its meter on the moving chronograph chart, which also is marked by two pens (one at each side of the chart) energized every second from a standard clock.

Procedure

For a test run on the watt-hour meters with the rectifier supply, the chronograph chart was started and allowed to record the meter revolutions for a period of eight minutes, during which the two indicating wattmeters were read every ten seconds, making a total of 48 readings each. Readings were taken every 30 seconds on each voltmeter and ammeter, giving a total of 16 readings per instrument. Thus one observer was required for each wattmeter, one for the three voltmeters, and one for the three ammeters, making a total of four.

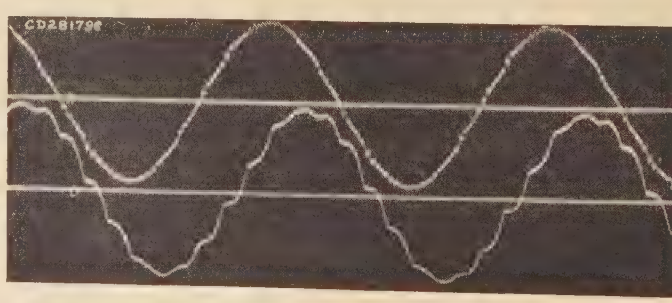
Next a test run was taken on the var-hour and power-factor meters and the chronograph chart was permitted to record the meter revolutions for five minutes, during which a total of 30 readings were taken on each of the two varmeters and on the power-factor meter and ten readings were taken on each voltmeter and ammeter. An extra observer was required for the power-factor meter.

The watt- and var-hour meter tests just described were checked by corresponding tests with the sine-wave supply, the secondary voltage, current, and power-factor values due to the rectifier load in each case being duplicated as closely as possible. The actual running time for the four tests at each load was 26 minutes.

Finally, the indicating watt (or var) meter readings taken in the a-c tests were checked with the d-c supply. Reversed readings were taken at each point, using two deflection potentiometers, one for voltage and the other for current, as standards.

After completing the tests, the readings of each indicating instrument were av-

Figure 7. Oscillogram showing wave shapes of voltage and current at 100 per cent output, 12-phase mercury-arc power rectifier rated type RDW, 3,000 kw, 625 volts



Curve *A*—Secondary voltage across lines 1–2

Curve *B*—Secondary current in line 1

Table IV. Actual and Estimated Percentages of Harmonics in A-C Input Waves

Test Number	Phases	Rectifier: Output (Per Cent)	Load Coefficient IX/E_0	Input (Average of Three): Kv	Input: Amp	Per Cent Harmonic — Harmonic Order and Frequency in Cycles Per Second: 1st 60	5th 300	7th 420	11th 660	13th 780	17th 1,020	19th 1,140	23d 1,380	25th 1,500	Oscillogram Figure Number
(1) Harmonic Analysis of Oscillograms															
Secondary current															
1	6	22	0.015	14.00	17.15	100	16.2	9.9	6.8	6.4	3.9	2.3			6.1
4	6	114	0.086	14.12	89.20	100	17.7	8.8	5.1	3.9	1.8	0.6			6*B*
6*a*	6	156	0.120	14.29	122.5	100	16.7	8.2	4.2	2.7		3.6			6*C*
Secondary voltage															
1	6	22	0.015	14.00	17.15	100	1.5	2.2	0.8	1.3	2.3				6*A*
4	6	114	0.086	14.12	89.20	100	1.7	1.1	2.2	2.8	0.6				6*B*
6*a*	6	156	0.120	14.29	122.5	100	2.9	3.6	2.3	1.8	2.1				6*C*
Secondary current															
†	12	100	0.058	14.00	126.0	100	1.4	0.5	5.0	3.8	0.4	0.1	0.9	0.7	7
Secondary voltage															
†	12	100	0.058	14.00	126.0	100	0.2	0.1	1.3	1.1	0.2	0.1	0.3	0.1	7
(2) Estimated Percentages of Harmonics in Current Waves Due to Rectifier															
(A) Light-load values (up to 25th harmonic)						Maximum Obtainable Per Cent Harmonics**									
	6	0–20	*			100	20	14.3	9.1	7.7	5.9	5.3	4.4	4.0	
	12	0–20	*			100			9.1	7.7			4.4	4.0	
(B) Full-load values						Per Cent of Light-Load Values									
	6	100	0.04			100	94	88	74	65	48	38	25	24	
	6	100	0.08			100	88	77	52	39	24	22	21	20	
	12	100	0.04			100			74	65			25	24	
	12	100	0.08			100			52	39			21	20	

* The load coefficient has a negligible effect on the magnitude of the harmonics at light load.

** Based on an inductive load; for a noninductive load, the fifth harmonic value is higher (= 22.6) but the other harmonic values are lower (or unchanged), so the maximum possible composite value is practically unchanged.

† Test made on 3,000-kw rectifier.

eraged and corrected for scale error. To obtain the three-phase volt-amperes, the three corrected voltmeter readings in each test were averaged, as were the three ammeter readings and these average values E and I were used in the formula.

$$\text{three-phase volt-amperes} = \sqrt{3}EI \qquad (9)$$

In each watt-hour meter test, the polyphase watts were obtained by adding the corrected readings of the two wattmeters and these indicated watts constituted the standard of reference in determining the meter accuracies. The recorded meter watts were determined from the total revolutions recorded on the chronograph chart and the corresponding elapsed time. The accuracy formula is

$$\text{per cent accuracy} = \text{recorded watts/indicated watts} \times 100 \qquad (10)$$

A similar procedure was followed for the var(rva)hour meter, the formula being

$$\text{per cent accuracy} = \text{recorded vars/indicated vars} \times 100 \qquad (11)$$

In these tests, however, the polyphase vars were obtained from the difference between the two varmeter readings. The reactive factor (sin "θ") was determined from the formula

$$\text{reactive factor} = \text{polyphase vars/volt-amperes} = Q/\sqrt{3}EI \qquad (12)$$

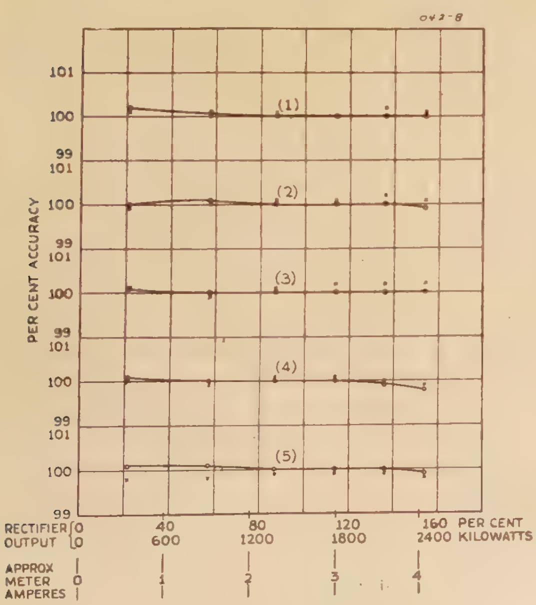


Figure 8 (left). Watt-hour-meter accuracies with six-phase rectifier and with sine-wave supply

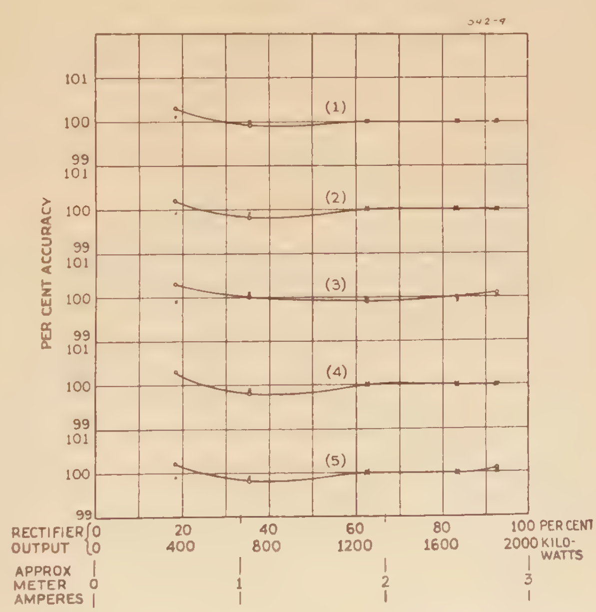
Figure 9 (right). Watt-hour-meter accuracies with 12-phase rectifier and with sine-wave supply

Curves 1, 2, 3—Type *DS*-19 meters

Curves 4, 5—Type *V*-3-*A* meters

Circles—Sine-wave supply

Crosses—With rectifier load



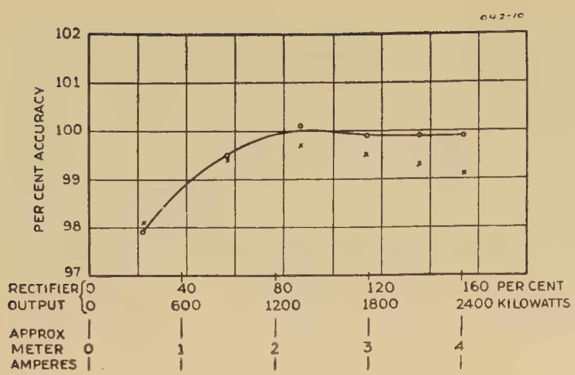


Figure 10. Accuracy of type DS-19 var (rva)-hour meter with six-phase rectifier and with sine-wave supply

Circles—Sine-wave supply
Crosses—Six-phase rectifier

Power factor ($\cos\theta$) was read directly on the power-factor-meter scale and for comparison was calculated from equation 2.

No corrections for the watts or vars were necessary because of the instrument transformers in the rectifier tests, since the meters were compared directly with the instruments in the secondary circuits.

Discussion of Results

Wave Shapes

A comparison of the current wave shapes in figure 6*A* at light load on the 6-phase rectifier with the theoretical waves, as shown by the magnitudes of the several harmonics in table IV, parts 1 and 2, indicates that the test harmonics are less than the theoretical ones by a maximum of about four per cent.

A much better agreement is found between the current wave shapes in figure 6*B* at rated output on the 6-phase rectifier and the theoretical waves based upon table IV, part 2*B*. The calculated harmonics check the test harmonics closely, the maximum difference being about two per cent for the seventh harmonic: the measured value is low. For the 12-phase rectifier, the agreement also is good, the maximum difference being less than one per cent. The load coefficient of the 6-phase rectifier approximates one assumed value (0.086 versus 0.08).

The corresponding harmonics in the voltage waves of both rectifiers are comparatively small, so the harmonic powers also are small; the probable maxima at rated output are indicated in table V. For the 6-phase rectifier, it should be noted that all harmonics above the 17th are omitted; also, that a harmonic in the order of the 49th appears in the voltage waves, due to the supply system. For both rectifiers, the system reactance was about 20 per cent of the total, so the harmonic voltage drops therein and the resulting harmonic powers are somewhat greater than would ordinarily be expected in service.

Meter Performance

The watt-hour-meter per-cent accuracies listed in table III have been corrected for minor errors in meter adjustment. For example, the actual test per-cent accuracies obtained for meter number 5 at 2.5 amperes in the sine-wave checks for both rectifiers were the same: 100.32, so 0.32 was subtracted from all test values. This procedure is equivalent to adjusting each meter to register correctly at its rated current of 2.5 amperes, in so far as comparative values are concerned. As just indicated, all results were carried out to the nearest 0.01 per cent and then rounded off to the nearest 0.1 per cent. The accuracy curves shown in figures 8 and 9 are quite flat and the differences between rectifier and corresponding sine-wave points are comparatively small.

Table V. Probable Maximum Harmonic Power at Rated Output

Order of Harmonic	6-Phase Rectifier* Per Cent of Line-to-Line Voltage	6-Phase Rectifier* Per Cent of Line Current	6-Phase Rectifier* Relative Harmonic** Volt-Amperes	12-Phase Rectifier* Per Cent of Line-to-Line Voltage	12-Phase Rectifier* Per Cent of Line Current	12-Phase Rectifier* Relative Harmonic** Volt-Amperes
1	100.0	100.0	10,000.0	100.0	100.0	10,000.0
5	1.7	17.7	30.1	0.2	1.4	0.3
7	1.1	8.8	9.7	0.1	0.5	0.1
11	2.2	5.1	11.2	1.3	5.0	6.5
13	2.8	3.9	10.9	1.1	3.8	4.2
17	0.6	1.8	1.1	0.2	0.4	0.1
19				0.1	0.1	0.0
23				0.3	0.9	0.3
25				0.1	0.7	0.1
Totals			10,063.0			10,011.6

* Harmonic values taken from table IV (1), 6-phase rectifier values from test number 4.

** Relative harmonic volt-amperes at an assumed power factor of unity equals relative harmonic power in watts.

Table V indicates that the probable maximum harmonic power for the 6-phase rectifier at rated output is about 0.6 per cent of the fundamental power; the corresponding values at 22 and 156 per cent output are 0.7 and 0.9 per cent, respectively. These apparent differences are not sufficient to account for the differences in effect on the meter speed. Although the phase relations of the several components of the harmonic power and therefore the true harmonic power itself at any output were not determined, there is no reason to expect that the net harmonic power changes sign as the rectifier output increases. In other words, there appears to be no correlation between the harmonic power and the rectifier effect. The probable maximum is less than 0.2 per cent for the 12-phase rectifier. It seems logical to conclude first, that the harmonic power due to 6- and 12-phase rectifiers will be comparatively small in practice and second, that their effect on the accuracy of modern watt-hour meters will be negligible.

Var-Hour and Power-Factor Meters

The var-hour-meter results are given in table III. The accuracy curve shown in figure 10 is fairly flat at the higher rectifier outputs, but it turns down toward light load; the differences between rectifier and sine-wave points are, in general, greater than for the watt-hour meters.

Table III also gives the power-factor-meter readings (*a*) and these agree fairly well with the corresponding values (*c*) calculated from equation 2. In fact it appears to be satisfactory to use this formula even if, as in these cases, there is some harmonic power, providing the circuit is balanced. Similarly, it appears to be satisfactory to use the formula

$$\text{volt-amperes} = \sqrt{\text{watts}^2 + \text{vars}^2} = \sqrt{P^2+Q^2} \quad (13)$$

to obtain the volt-amperes in the circuit,

when not otherwise available. The ratio measured/calculated volt-amperes as obtained from equations 9 and 13, respectively, should approximate ratio (3) whenever the harmonics in the balanced voltage waves are small. This also applies to the ratio of power factors calculated from equations 2 and 1.

The average value of ratio (3) in 6-phase rectifier test numbers 1, 4, and 6a is 1.021 (from table IV, part 1). This compares with 1.025, which represents the average ratio for the same three tests between the two calculated power factors (table III, (c) and (b)). It appears that the voltage harmonics do not exert an appreciable effect.

It has been emphasized that the type P-3 power-factor meter is for use on balanced circuits only. In these tests, the circuit balance cannot be determined from the tables, as the averages of the voltages and currents instead of the individual values are given to conserve space. In general, excellent balance was obtained in the six-phase rectifier tests and in the corresponding sine-wave check tests, the maximum difference between any of the three voltages or between any of the three currents being in the order of one per cent.

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Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Transient Analysis of Symmetrical Networks by the Method of Symmetrical Components

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Synopsis: The canonical equations of a general, linear, bilateral symmetrical network of n meshes on which are impressed arbitrary mesh voltages are subjected to a Laplacian transformation. The transformed equations are then subjected to a symmetrical component transformation. By the use of these transformations the transient behavior of an n mesh symmetrical network subject to impressed arbitrary voltages and initial currents and charges is readily obtained. The solution of the usual determinantal equation is avoided.

SINCE the introduction of the method of symmetrical components into electrical engineering by Fortescue in his classic paper,[1] there have been many extensions and expositions of the method.[2,3] It appears however, that no systematic exposition of the use of symmetrical components in the study of transients in linear, constant, bilateral symmetrical networks has appeared. It is the purpose of this discussion to present such an exposition. The methods of the Laplacian transformation and matrix algebra as presented in references 4 and 5 respectively will be assumed.

I. The Canonical Equations

Let us consider a general, linear, constant, bilateral, lumped n-mesh network. Let the n mesh currents have the instantaneous values $(i_1 \ldots i_n)$ and let there be n voltages $(e_1 \ldots e_n)$ acting on the contours of the n meshes. The canonical equations of such a general n-mesh circuit may be written in the form:

$$(e) = [Z](i) \tag{1}$$

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1. For all numbered references, see list at end of paper.

Where (e) and (i) are columnar matrices whose elements are the n mesh voltages and currents respectively and $[Z]$ is a square matrix of the nth order whose elements are the various self and mutual impedance operators of the form:

$$Z_{rs} = L_{rs}d/dt + R_{rs} + S_{rs}\int_{-\infty}^{t} (\ )dt \tag{2}$$

and L_{rs}, R_{rs}, S_{rs} are the coefficients of self- and mutual inductance, resistance, and elastance of the system. The impedance operator matrix $[Z]$ has the important property of being symmetrical about the principal diagonal. This property follows from the relations:

$$L_{rs} = L_{sr} \tag{3}$$

$$R_{rs} = R_{sr} \tag{4}$$

$$S_{rs} = S_{sr} \tag{5}$$

II. E-Symmetric Systems

Many networks of practical importance have the property that their impedance operators satisfy the relations:

$$Z_{11} = Z_{22} = \ldots\ldots = Z_{nn} = Z_0 \tag{6}$$

$$Z_{sr} = Z_{jk} = Z \text{ for } r \neq s,\ j \neq k \tag{7}$$

that is, the impedance matrix of these systems has the form:

$$[Z] = \begin{Vmatrix} Z_0 & Z & Z & Z \ldots Z \\ Z & Z_0 & Z & Z \ldots Z \\ \ldots & \ldots & \ldots & \ldots \\ Z & Z & Z & Z \ldots Z_0 \end{Vmatrix} \tag{8}$$

Such networks have equal self-impedance operators among the several meshes and also equal mutual impedance operators between the meshes. Networks exhibiting this type of symmetry are called E-symmetric and are of great technical importance. Symmetrical polyphase systems are of this type.

III. The Laplacian Transformation of the Canonical Equations

Following the method of (5) part II, we subject the canonical matrix equation

(1) to a Laplacian transformation as follows:
Let

$$I_j(p) \div i_j(t) \qquad (I) \div (i) \qquad (9)$$

$$E_j(p) : e_j(t) \qquad (E) \div (e) \qquad (10)$$

that is, for each element of the current matrix (I) and the voltage matrix (E) of (1) we introduce its Laplacian transform. Then the matrix equation (1) is transformed into:

$$[Z(p)](I) = (E) + p[L](i^0) - [S](q^0) \qquad (11)$$

where:

$$(i^0) = \begin{Vmatrix} i_1^0 \\ i_2^0 \\ \dots \\ i_n^0 \end{Vmatrix} \qquad (12)$$

and ($i_1^0 \dots i_n^0$) are the initial mesh currents at $t=0$ in the system,

$$(q^0) = \begin{Vmatrix} q_1^0 \\ q_2^0 \\ \dots \\ q_n^0 \end{Vmatrix} \qquad (13)$$

($q_1^0 \dots q_n^0$) represent the n initial mesh charges at $t = 0$.

$$Z_{mn}(p) = L_{mn}p + R_{mn} + S_{mn}/p \qquad (14)$$

$[L] = [L_{mn}]$ the inductance matrix (15)

$[S] = [S_{mn}]$ the elastance matrix (16)

IV. Transformation to Symmetrical Components

In the theory of symmetrical components,[1] the transformations are effected by the use of the nonsingular, symmetric matrix:

$$[C] = [C_{rs}] \qquad (17)$$

where

$r = 1, 2, \dots n$
$s = 1, 2, \dots n$

$$C_{rs} = a^{-(r-1)(s-1)} \qquad (18)$$

$$a = \epsilon^{j2\pi/n} \qquad (19)$$

The transformation matrix $[C]$, is thus a square matrix of the nth order with the important properties that:

$$[C]' = [C] \qquad (20)$$

where $[C]'$ is the transpose matrix of $[C]$

$$[C]^{-1} = \frac{1}{n}[\text{conj } C] \qquad (21)$$

where $[C]^{-1}$ is the inverse of $[C]$ and [conj C] is the conjugate of $[C]$. The rows of $[C]$ are the sequence operators of Fortescue.

Let us now multiply both sides of the equation (11) on the right by $[C]^{-1}$. We then obtain:

$$[C]^{-1}[Z][C][C]^{-1}(I) = [C]^{-1}(E) + p[C]^{-1}[L][C][C]^{-1}(i^0) - [C]^{-1}[S][C][C]^{-1}(q^0) \qquad (22)$$

Now let us introduce the notation:

$$(E)_s = [C]^{-1}(E) \qquad (23)$$

$$(I)_s = [C]^{-1}(I) \qquad (24)$$

$$[Z]_s = [C]^{-1}[Z][C] \qquad (25)$$

$$[L]_s = [C]^{-1}[L][C] \qquad (26)$$

$$[S]_s = [C]^{-1}[S][C] \qquad (27)$$

Then equation 22 may be written in the form:

$$[Z]_s(I)_s = (E)_s + p[L]_s(i^0)_s - [S]_s(q^0)_s \qquad (28)$$

V. Transformation of the E-Symmetric System

Let us consider the transforms of the equations of the E-symmetric system of part II. In this case, the impedance matrix has the form given by (8). Computation of the symmetrical component matrix of the E-symmetric system by the equation (25) gives:

$$[Z]_s = \begin{Vmatrix} Z_0+(n-1)Z & 0 & 0\dots & 0 \\ 0 & (Z_0-Z) & 0\dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & 0\dots & (Z_0-Z) \end{Vmatrix} \qquad (29)$$

that is, the symmetrical component transformation matrix $[C]$, transforms the impedance matrix of the E-symmetric network into the diagonal form (29).

Let:

$$(I)_s = \begin{Vmatrix} I_{1s} \\ I_{2s} \\ \dots \\ I_{ns} \end{Vmatrix} = [C]^{-1} \begin{Vmatrix} I_1 \\ I_2 \\ \dots \\ I_n \end{Vmatrix} \qquad (30)$$

and, similarly introduce the columnar matrices:

$$(E)_s = (E_{rs}) = [C]^{-1}(E_r) \qquad (31)$$

$$(i^0)_s = (i_{rs}^0) = [C]^{-1}(i_r^0) \qquad (32)$$

$$(q^0)_s = (q_{rs}^0) = [C]^{-1}(q_r^0) \qquad (33)$$

then the equation (28) separates into the n scalar equations:

$$[Z_0+(n-1)Z]I_{1s} = E_{1s} + p[L_0 + (n-1)L]i_{1s}^0 - [S_0+(n-1)S]q_{1s}^0 \qquad (34)$$

$$(Z_0-Z)I_{rs} = E_{rs} + p(L_0-L)i_{rs}^0 - (S_0-S)q_{rs}^0 \qquad (35)$$

$r = 2, 3, \dots n$

We then have immediately:

$$I_{1s} = E_{1s}/[Z_0+(n-1)Z] + p[L_0+(n-1)L]i_{1s}^0/[Z_0+(n-1)Z] - [S_0+(n-1)S]q_{1s}^0/[Z_0+(n-1)Z] \qquad (36)$$

$$I_{rs} = E_{rs}/(Z_0-Z) + p(L_0-L)i_{rs}^0/(Z_0-Z) - (S_0-S)q_{rs}^0/(Z_0-Z) \qquad (37)$$

$r = 2, 3, \dots n$

Now if we let:

$$(i)_s \div (I)_s \qquad (38)$$

that is:

$$i_{rs} : I_{rs} \qquad (39)$$

$r = 1, 2, \dots n$

We may compute the i_{rs} quantities from (36) and (37). We also have the relations:

$$(I) = [C](I)_s \qquad (40)$$

and

$$(i) : (I) \qquad (41)$$

Hence if we premultiply (38) by $[C]$ we obtain:

$$[C](i)_s \div [C](I)_s = (I) : (i) \qquad (42)$$

or finally,

$$(i) = [C](i)_s \qquad (43)$$

and we have the various currents explicitly.

VI. Examples

Let us consider the application of the above general theory to specific examples.

Discharge of a Capacitor in One of Two Mutually Influencing Circuits

Suppose that we have two similar circuits each with self-induction L_0 and elastance S_0, but negligible resistance, and that the capacitor in one carries an initial charge q^0. The initial currents in the system and the charge on the capacitor of the second circuit are supposed to be equal to zero. The coefficient of mutual induction is M. The problem is to determine the subsequent behavior of the system.

In this case we have:

$$[Z] = \begin{Vmatrix} Z_0 & Z \\ Z & Z_0 \end{Vmatrix} \qquad (44)$$

with:

$$Z_0 = L_0p + S_0/p \qquad (45)$$

$$Z = Mp \qquad (46)$$

Since we have no impressed electromotive forces and no initial currents, the equations (36) and (37) for this circuit reduce to the following:

$$I_{1s} = -S_0q_{1s}^0/(Z_0+Z) \qquad (47)$$

$$I_{2s} = -S_0q_{2s}^0/(Z_0-Z) \qquad (48)$$

in view of the fact that $n=2$ and $S=0$.

The transformation matrix C and its inverse for this case is given by:

$$[C]=\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix} \tag{49}$$

$$[C]^{-1}=\frac{1}{2}\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix} \tag{50}$$

we thus have:

$$\begin{Vmatrix}q_{1s}^0\\ q_{2s}^0\end{Vmatrix}=\frac{1}{2}\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix}\begin{Vmatrix}q_1^0\\ 0\end{Vmatrix}=\frac{1}{2}\begin{Vmatrix}q_1^0\\ q_2^0\end{Vmatrix} \tag{51}$$

since the second circuit does not have an initial charge. To simplify the operations, let us write:

$$M=L_0b \tag{52}$$

$$S_0=L_0c^2 \tag{53}$$

We then have the following equations for I_{1s} and I_{2s}:

$$I_{1s}=-c^2pq_{1s}^0/[p^2(1+b)+c^2]=-\frac{1}{2}c^2q_1^0p/(1+b)[p^2+c^2/(1+b)] \tag{54}$$

$$I_{2s}=-\frac{1}{2}c^2q_1^0p/(1-b)[p^2+c^2/(1-b)] \tag{55}$$

If we now make use of the basic transform:

$$p/(p^2+w^2)\div \sin(wt)/w \tag{56}$$

we obtain:

$$i_{1s}=-\frac{1}{2}\frac{cq_1^0}{\sqrt{1+b}}\sin(ct/\sqrt{1+b}) \tag{57}$$

$$i_{2s}=-\frac{1}{2}\frac{cq_1^0}{\sqrt{1-b}}\sin(ct/\sqrt{1-b}) \tag{58}$$

The actual currents in the two circuits i_1 and i_2 are now obtained from the symmetrical-component currents i_{1s} and i_{2s} by the transformation:

$$\begin{Vmatrix}i_1\\ i_2\end{Vmatrix}=\begin{Vmatrix}1 & 1\\ 1 & -1\end{Vmatrix}\begin{Vmatrix}i_{1s}\\ i_{2s}\end{Vmatrix} \tag{59}$$

or hence:

$$i_1=-\frac{1}{2}cq_1^0[(1/\sqrt{1+b})\sin(ct/\sqrt{1+b})+(1/\sqrt{1-b})\sin(ct/\sqrt{1-b})] \tag{60}$$

$$i_2=-\frac{1}{2}cq_1^0[(1/\sqrt{1+b})\sin(ct/\sqrt{1+b})-(1/\sqrt{1-b})\sin(ct/\sqrt{1-b})] \tag{61}$$

We thus obtain the current in the two meshes without solving for the roots of the characteristic equation of the system which in this case is one of the fourth order.

Application to Three-Mesh Network

Let us consider an E-symmetric three-mesh network. Let each mesh have a mesh inductance L_0 and mesh elastance S_0. Let the three meshes be coupled together by equal mutual inductance coefficients M.

The network will be considered inert at $t=0$, that is, the mesh currents and mesh charges are zero at $t=0$. At $t=0$, a steady electromotive force E is impressed on mesh one. The problem is to determine the subsequent currents in the three meshes.

For this case, the impedance matrix of the network is given by:

$$[Z]=\begin{Vmatrix}Z_0 & Z & Z\\ Z & Z_0 & Z\\ Z & Z & Z_0\end{Vmatrix} \tag{62}$$

with:

$$Z_0=L_0p+S_0/p \tag{63}$$

$$Z=Mp \tag{64}$$

The general equations (36) and (37) in this case reduce to:

$$I_{1s}=E_{1s}/(Z_0+2Z) \tag{65}$$

$$I_{2s}=E_{2s}/(Z_0-Z) \tag{66}$$

$$I_{3s}=E_{3s}/(Z_0-Z) \tag{67}$$

Now, since the electromotive force impressed in mesh number 1 is steady, we have:

$$\begin{Vmatrix}E_{1s}\\ E_{2s}\\ E_{3s}\end{Vmatrix}=\frac{1}{3}\begin{Vmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{Vmatrix}\begin{Vmatrix}E_1\\ 0\\ 0\end{Vmatrix}=\begin{Vmatrix}E_1\\ E_1\\ E_1\end{Vmatrix} \tag{68}$$

where:

$$a=\epsilon^{j2\pi/3} \tag{69}$$

Hence we have:

$$I_{1s}=\frac{1}{3}E_1p/[p^2(L_0+2M)+S_0] \tag{70}$$

$$I_{2s}=\frac{1}{3}E_1p/[p^2(L_0-M)+S_0]=I_{3s} \tag{71}$$

Now if we let:

$$w_1=\sqrt{S_0/(L_0+2M)} \tag{72}$$

$$w_2=\sqrt{S_0/(L_0-M)} \tag{73}$$

then, in view of the transform relation:

$$p/(p^2+w^2)\div \sin(wt)/w \tag{74}$$

we obtain the following expressions for the transforms of I_{1s}, I_{2s}, and I_{3s}.

$$i_{1s}=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)} \tag{75}$$

$$i_{2s}=\frac{1}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)}=i_{3s} \tag{76}$$

The actual three mesh currents of the system are now obtained by the equation:

$$\begin{Vmatrix}i_1\\ i_2\\ i_3\end{Vmatrix}=\begin{Vmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{Vmatrix}\begin{Vmatrix}i_{1s}\\ i_{2s}\\ i_{3s}\end{Vmatrix} \tag{77}$$

Carrying out the matrix multiplication, we obtain:

$$i_1=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)}+\frac{2}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)} \tag{78}$$

$$i_2=\frac{1}{3}E_1\sin(w_1t)/\sqrt{S_0(L_0+2M)}-\frac{1}{3}E_1\sin(w_2t)/\sqrt{S_0(L_0-M)}=i_3 \tag{79}$$

We thus obtain the solution to our problem in a most simple manner. It may be remarked that had we proceeded in the conventional operational manner, we would have been forced to determine the roots of a sixth order algebraic equation in order to apply the Heaviside expansion formula. A transformation to symmetrical components avoids all this labor.

VII. Conclusion

The general equations by which the transient analysis of multimesh E-symmetric networks may be carried out have been developed. The introduction of symmetrical component and Laplacian transformations enormously simplify the analysis of this type of networks. Since E-symmetric networks are of great technical importance in many branches of engineering, it is hoped that this contribution to their theory will be of value. The method may be readily applied to all linear dynamical systems exhibiting this type of symmetry whether electrical or mechanical.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

The Accuracy of Watt-Hour Meters on Intermittent Loads

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Synopsis: A watt-hour meter on intermittent loads of a particular character may have a registration error. The magnitude of error is a function of the meter design, the periodicity of the intermittent component of load, ratio of intermittent component to total load, character of intermittent component, power factor of load, and adjustment of the friction compensation.

The registration characteristic of a meter on most types of intermittent load can be predicted from the acceleration and deceleration curves for the meter disk.

THE characteristics of watt-hour meters are dependent upon many diverse factors interrelated in a complex way. The design of the magnetic circuits, the mechanical features of the meter, and the various corrective elements to a large degree are responsible for these diverse factors. Once in service, however, the characteristics of a meter are relatively fixed, except as influenced by the remainder of the circuits with which it is associated.

The nature of the load which is to be measured by the meter may have an important effect on the characteristic performance of the meter. Loads may vary continually in magnitude or be intermittent with the period of cyclic variation from a few cycles to many minutes or hours. Such intermittent loads may cause factors which are usually of relatively minor importance to have considerable influence on the meter accuracy. Since these factors are interrelated, it is difficult to separate them experimentally, and only their combined effects have been studied.

In the usual application of watt-hour meters, the intermittent nature of the load will affect only those factors which depend upon the magnetic effects produced by the current elements or series coils, the potential element being energized at all times, thus making its effects constant. However, some adjustments of the meter which are independent of the series coil may affect the meter performance because of the interdependence of those factors and their influence on the common sections of the magnetic circuit.

The results of this study are given in curve form and are representative of several meters operating under the same load conditions. A careful study of the starting and stopping characteristics was made photographically. These results were verified by actual load tests.

Results of Study With Discussion

The registration of a watt-hour meter is a direct measure of the total angular travel of the meter disk. This angular travel, in turn, is a function of the angular velocity of the disk and time. The angular velocity of the disk for a given load is dependent upon the mechanical and geometrical factors of the moving system and the summation of the various component torques (driving and retarding) acting on this moving system.

It has been shown that the mechanical and geometrical factors for a given meter are essentially constant. As indicated in the appendix, the various component torques are constant when the load on the meter is constant, but for a variable load, the various component torques do not remain constant during the transitory periods. Certain torque factors which are present during the acceleration period of the meter disk may not be present during the deceleration period. The relative magnitudes of these changing torques will determine the meter accuracy during the transition period from one load value to another.

Figure 1 shows the accelerating and decelerating characteristic curves for a typical modern meter.* These curves are representative of those obtained from a stroboscopic photographic recording of the meter-disk travel during the period of change from rest to constant angular velocity and from constant angular velocity to rest. It will be noted that the slope of the constant-velocity sections changes in accordance with the different loads. Data for these curves were obtained by scaling angular travel of the meter disk from successive photographs of the disk obtained by means of a stroboscopic camera. The time interval between successive photographs was controlled accurately. The time or angular travel necessary for a disk to attain constant velocity was obtained by drawing a tangent to the curve at a slope corresponding to the velocity attained.

In an ideal meter in which no torque component is a function of higher than the first power of the disk angular velocity (appendix) and in which the ultimate disk velocity is directly proportional to the load, the time required to attain any given per cent of ultimate velocity is not a function of the load. In a practical meter, however, these conditions are not fulfilled although they are approximated closely. The position of the anticreep slots at the start of the acceleration period, the flux density in the various portions of the magnetic circuit, reactions of disk currents on the distribution of the flux in the various paths, and the variation of the friction torque with disk velocity are some of the factors which can produce small effects in a practical case. The accurate determination of the time required to attain steady-state condition is not necessary, an approximation being sufficient to indicate the character of intermittent loads which may give rise to registration errors. The graphical method of determining the point of tangency has inherent errors larger than the probable error due to the causes listed above.

The time required for the disks of meters of different designs to reach a constant angular velocity differs, the limits being approximately 0.2 second and 0.4 second. The time required for the disk to reach rest from the constant angular velocity corresponding to rated load is from 0.3 to 0.4 second. These variations between meters of different designs can be attributed to the fact that the components of torque are not in the same proportions in the different meters. It should be noted, however, that the time required is of interest only in the examination of a load cycle. The accuracy with which the meter integrates a load over a cycle depends upon the total disk travel during the cycle and not upon the time required for that travel.

If a constant load is placed on a meter

* Both the modern and the older design of meters were used in the experimental tests.

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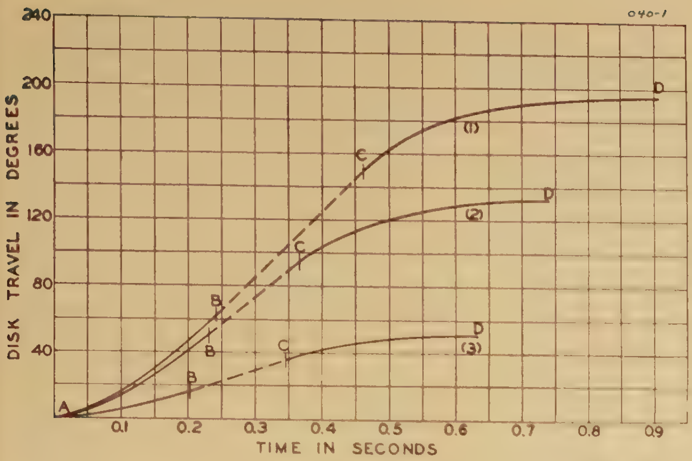


Figure 1. Acceleration characteristics of a typical watt-hour meter for various loads at unity power factor

A–B—Acceleration period
B–C—Constant-velocity period
C–D—Deceleration period

Curve 1—300 per cent load
Curve 2—250 per cent load
Curve 3—100 per cent load

a sufficient time to allow the meter disk to start from rest and attain constant angular velocity and then is removed for the length of time required for the meter disk to return to rest, the total angular travel of the disk should be a direct measure of the energy involved in the load cycle. This total disk travel should be equal to the product of the constant velocity and the time the load is applied if this registration is a correct measure of the energy. During the period of acceleration up to the velocity corresponding to the load value, the disk has lost a definite number of degrees of travel since it must start from rest and its average velocity during this accelerating period is less than the constant value corresponding to this load. After the load is removed, the disk decelerates to rest and gains a definite number of degrees of travel. If the number of degrees lost during the acceleration period does not equal the number gained during the deceleration period the meter registration is in error. This error in registration will be positive or negative in accordance with too large or too small a gain in disk travel at the end of a load cycle compared to the beginning. It will be indicated later that this error is influenced by the design of the meter and its adjustments for constant load accuracy.

If the load exists for a longer time than is necessary for the disk to attain the velocity corresponding to the load, the disk will travel at constant velocity for the time in excess of that required to reach this load velocity. The disk travel to rest after the load is removed will be the same for a given disk velocity regardless of the time the meter has been running at this velocity. The error in registration (degrees of travel) will be the same for each load cycle, but the per cent error in total registration will approach that for a constant load.

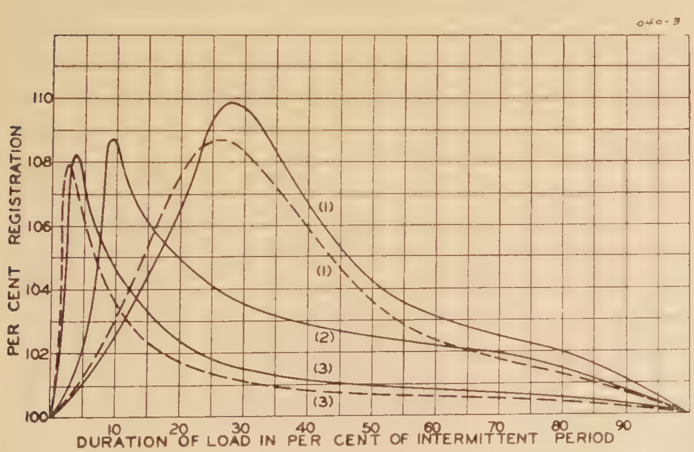


Figure 3. Comparison of predicted and test curves of watt-hour meter accuracy for intermittent loads of different periods

Predicted curves are in solid lines
Test curves are in dotted lines

Curve 1—8-cycle period
Curve 2—35-cycle period
Curve 3—100-cycle period

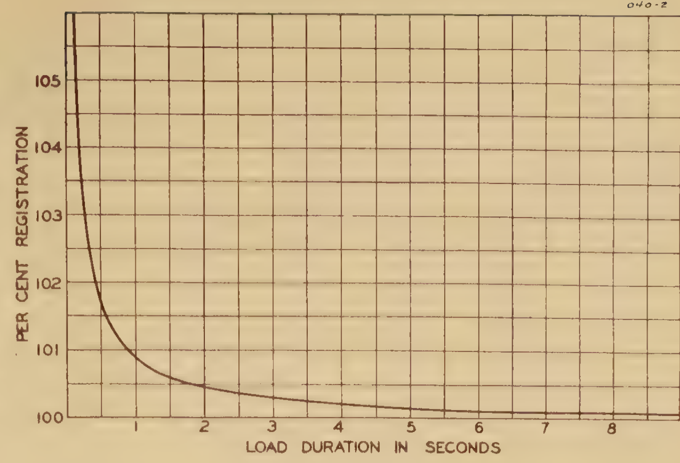


Figure 2. Effect of load duration on watt hour meter accuracy for 200 per cent load a unity power factor

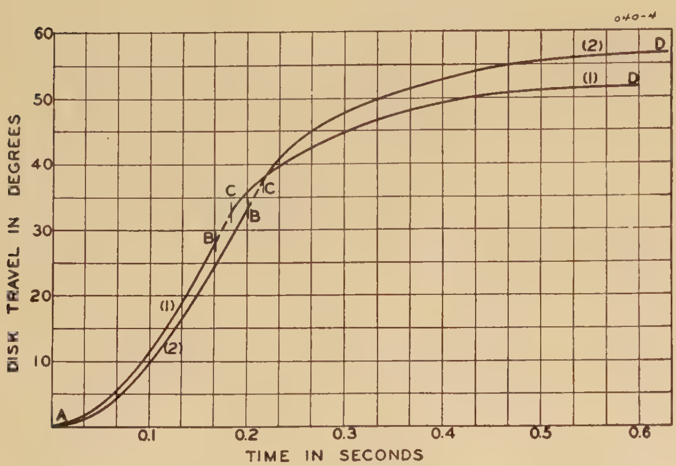
The effect of the length of the constant velocity period on the total registration of the meter is shown in figure 2. This curve is obtained from curves such as given in figure 1. The curve of figure 2 is for approximately 200 per cent load, unity power factor on the meter. As the constant-velocity interval is increased for a given load, the per cent error is reduced. It will be noted that for load durations less than one second, the meter error, caused by intermittent load, is one per cent or more and, for very short duration loads, will exceed five per cent. If the load duration is greater than four seconds, the intermittent load cycle causes an error less than one-fourth per cent. This error is within the limits of commercial meter accuracy.

For practically all types of intermittent loads, the approximate registration characteristics of the meter may be predicted, from the acceleration and deceleration curves (figure 1) for the meter. These characteristics should be at the power factor and with the same wave form as would be encountered in the circuit under consideration. For any load-variation cycle in which the load decreases to zero the approximation may be very close if the acceleration curves are known for each value of load and the deceleration curve is known for the greatest value of load to be considered in the group of loads studied. The degree of approximation (in predicting the registration characteristics) for other load cycles depends upon the relative value of the variable and fixed components of the load. The approximation is least accurate when the fixed com-

ponent becomes a major part of the total load.

For a simple case of approximately full load of unity power factor either fully on or off, with the period of the load cycle of value indicated, the registration characteristics of a typical meter as a function of the per cent of the total period during which the load exists are shown in figure 3. These curves are derived from characteristics such as given in figure 1. Curves from experimental data for the same meter in a circuit with a load having periods of 8 and 100 cycles are shown for comparison.

With the characteristic curves for the meter available, for the loads chosen, such curves as those in figure 3 may, for simple load cycles, be predicted with ease. Beginning with the disk at rest the acceleration disk-travel curve is drawn for the length of time corresponding to the "on" portion of the load cycle. This curve is then extended by use of the deceleration disk-travel curve from the point on that curve having the same slope as the acceleration curve at the end of the first "on" portion. The deceleration curve is used for a time corresponding to the "off" portion of a load cycle. The acceleration curve is then applied as before except that the velocity at the end of the previous "off" period must be used to determine the initial conditions for the new "on" period. Successive "on" and "off" conditions must be assumed until the disk travel in any single load cycle becomes a constant value. This travel is compared with the proper value (constant velocity times the "on" time) and the registration noted as compared to the



A–B—Acceleration period
B–C—Constant-velocity period
C–D—Deceleration period
Curve 1—100 per cent power factor
Curve 2—63 per cent power factor

Figure 4. Acceleration characteristics of a typical watt-hour meter for 200 per cent load at two different power factors

proper value. The number of these load cycles necessary to have "steady state" will depend upon the meter and the choice of load cycle and may be as many as 10 or 15 load cycles.

For complex load cycles the same procedure can be followed except that the proper characteristic curves must be used for the acceleration portions of the travel curve, and deceleration curves for partial removal of loads should be available. None of these deceleration characteristics for partial removal of loads has been included in the data of this investigation.

The experimental check was obtained by applying intermittent loads of a definite nature and comparing the actual registration of the meter for a known number of cycles "on" with the registration of the meter for the same number of cycles "on" for a continuous load of the same magnitude, power factor, and wave form. These check load cycles were chosen to correspond to those for which the errors were predicted from characteristic curves.

The predicted curves of figure 3 are for sinusoidal voltage and current variations. The experimental circuit currents correspond closely to that of a continuous welder. The harmonics in such load currents may be expected to influence the registration of the meter to some extent. Experimental investigation of this factor by the authors in the case of continuous loads indicates that the effects of such proportions of harmonics as are present in those load currents will not introduce an appreciable error in registration. The influence of this factor on the registration of a meter on intermittent loads should be very nearly the same as for constant loads having the same wave shape since the same torque factors would be affected by the harmonic components. For loads of short periodic duration, the effect of the corrective adjustments also is important. The light load compensation should be carefully adjusted, otherwise its effect will influence the shape of the registration curve. See paragraph (*b*) of the next section.

It will be noted that the maximum error in registration of the meter, used as an illustration, occurs when the duration of the load is from two to four cycles. Certain welder controls are commonly set for this period of operating time in order to give the proper working conditions for the materials being processed. It will be noted that the magnitude of the predicted maximum error is nearly independent of the period of load. This is borne out by the experimental results. Tests have indicated that, in the older designs of meters, this error is greater than in the more modern meter designs. This, no doubt, is caused by a different relationship between the various torque components in these classes of meters.

In some of the meters tested, when adjusted within the limits of accepted commercial accuracy, this maximum error was as great as 20 per cent. More than normal care in adjusting the meters resulted in the marked reductions in the maximum error.

The registration error due to intermittent load must approach zero as the acceleration portion of the load cycle approaches zero or 100 per cent of the load cycle. At some other value of the duration of load the error must be a maximum. The per cent of the intermittent period at which the maximum error occurs depends upon the design of the meter and the length of the intermittent period. The curves of figure 3 illustrate a simple load cycle with the load completely on or off. For other load cycles other registration curves would be obtained.

Effects of Power Factor, Light-Load Adjustments, and Wave Shape

(*a*) *Power Factor*. The power factor of an intermittent load will influence the relative values of the accelerating and decelerating torques. This influence may be divided further into (1) effects on driving torque, (2) effect on friction-compensating torque, and (3) effect on current-damping torque. The exact influence of power factor on each is not known quantitatively but it may be shown (see appendix) that these three torque components may be affected. The driving torque per ampere will be

decreased as the power-factor angle is increased. This in turn may affect indirectly the friction compensation because of a new resultant flux per unit of driving torque. The new resultant flux may be shifted in time phase relative to the original flux, which may cause a change in the magnitude of the friction-compensating torque.

The effect of power factor on the current-damping torque is a function of current-coil flux. The flux will increase as the current increases but in a proportion which is dependent on the properties of the magnetic circuit. The effect at normal current values will be approximately in proportion to the current change per unit of power.

The net effect of small changes in power factor alone on the intermittent-load characteristic of the meter is ordinarily a minor one, because of the small net changes which occur in the total torques. Figure 4 shows the starting and stopping characteristic curves for a meter at two widely different power factors. The curve at the lower power factor indicates a longer time required to reach constant velocity from rest for the same load but the decelerating periods are the same. The elapsed time for a complete start-stop cycle is greater at the lower power factor and as a result the total travel of the disk is greater for the complete cycle. This increased time for a complete start-stop cycle will affect the meter performance on very short interval loads where the meter does not reach the true load velocity. For the loads of longer duration the error in starting and stopping is decreased and it is quite possible to have a meter with a combination of torque values which will give correct registration at some low power factor. Depending upon the adjustments of a meter, low lagging power factor loads may cause the registration error to become negative.

(*b*) *Light-Load Adjustments.* The curves which have been shown (figures 1, 2, 3, and 4) have been determined with the light-load adjustments as carefully adjusted as possible for all the meters used in these tests. The influence of this light-load compensation and how it can affect the meter performance on intermittent load is indicated by the registrations at three different positions of the light-load compensator for the same meter load. This influence is indicated in figure 5. The three points on the curve for this periodic load (three cycles on and five cycles off) are for the compensator positions of (1) ready to creep backward, (2) mid-position of compensator, and (3) ready to creep forward. The mid-position of the friction compensator corresponds very closely to the actual position used when this meter was in the original test circuits. Several test runs were made with the compensator at various positions and for intermittent loads of different periodic durations. It can be inferred from figure 5 that the component of torque from the compensator will be of great importance for loads of short periodic duration but will be less important as the period becomes longer. It is believed that more than ordinary care should be exercised in adjusting the compensator if the meter is to be used on a circuit which has a transitory load of major importance and of comparatively short periodicity.

(*c*) *Wave Shape.* Care was exercised in making comparisons between the performances for different load durations, that the wave shapes of the current and voltage were constant. The study of the effects of wave shape is separate and apart from this load study, but tests have been made which show that wave shape will influence the registration of a meter

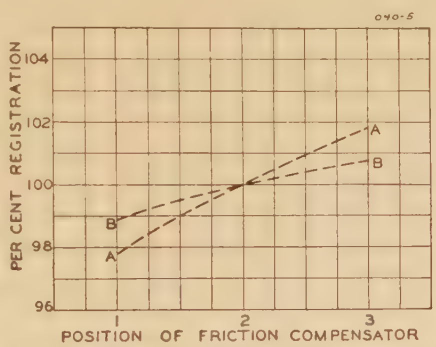


Figure 5. Effect of friction-compensator position on watt-hour meter accuracy for intermittent loads of short duration

A–A—One cycle on and seven cycles off
B–B—Three cycles on and five cycles off

and for that reason only performance curves for the same wave shapes were compared in determining the meter accuracy.

Conclusions

1. The stroboscopic photographic data of the meter accelerating and decelerating characteristics can be used to predict with a good degree of accuracy the performance characteristics on most types of intermittent load. This is indicated by the comparison of the predicted and the actual test curve shown in figure 3.

2. The relative effects of the various torques influence the registration of a meter. If the speed of the disk is low, as in the present-day meter, the retarding torques will maintain a fairly uniform relationship. The current-damping torque has less relative effect in the modern meter and as a result, the accuracy on intermittent load has been improved.

3. The character of the load cycle, that is, the time the load is on and the time the load is off, influences the registration of the meter. Tests indicate that the conditions for maximum error occur at two to four cycles of accelerating period. This maximum error may be as much as 20 per cent. The off period apparently is not so important.

4. The adjustment of the light-load compensation is extremely important and care must be taken to be certain that there is minimum friction in the moving system of the meter, in order that friction-compensation-torque value may be minimized. If the adjustment is such that the meter is on the verge of creeping, an error up to 30 per cent may be obtained.

5. The variation of an intermittent load may be of a small magnitude in comparison with the average value of the load. In this case the influence of the load variation will be negligible.

6. Tests indicate that the load power factor influences the registration error. However, the damping effect of the current flux is relatively small in the modern meter, and the power factor of the load does not affect the meter accuracy on intermittent loads as much as in meters of older design.

7. The increased overload rating and increased ratio of driving torque to the moment of inertia of the moving element have decreased the accelerating time for a given load change. This improvement has decreased the meter error on intermittent load from the values found in the older designs of meters.

8. For metering loads which are continually transitory in nature, it is suggested that present-day meters be used and that a careful study of the load be made. Loads, such as electric welder and flashing electric-sign loads, should be carefully studied before being metered as a single load on a meter.

Appendix

When a watt-hour meter is recording a constant load at a constant speed, the total driving torque equals the total retarding torque. The relationship can be expressed in equation form as:

$$(T_D+T_L)-(T_M+T_P+T_C+T_F)=0$$

where

T_D = driving torque produced by the interaction of the potential-coil and current-coil fluxes
T_L = driving torque of the light-load (friction) compensator
T_M = retarding torque of the permanent magnets
T_P = potential-flux retarding torque
T_C = current-flux retarding torque
T_F = retarding torque of friction

In order to indicate the relative importance and effect of each term the controlling factors of each torque are indicated. Thus, the torque equation becomes:

$$k_1 f[\underbrace{(f)\phi_P\phi_C \sin \alpha}_{1}+\underbrace{(f)\phi_P^2 \sin \beta}_{2}]-\frac{k_1}{2} f_d[\underbrace{(f)\phi_M^2}_{3}+\underbrace{(f)\phi_P^2}_{4}+\underbrace{(f)\phi_C^2}_{5}]-\underbrace{[k_f(f)f_d+F_0]}_{6}=0$$

Part 1 = T_D expressed as a function of potential flux, current flux, and the angle of displacement between them

Part 2 = T_L expressed as a function of the square of the potential flux and the angle of displacement between the resultant flux and potential flux

Part 3 = T_M expressed as a function of permanent-magnet flux

Part 4 = T_P expressed as a function of potential flux

Part 5 = T_C expressed as a function of current flux

Part 6 = T_F expressed as a function of disk speed plus a friction-torque component independent of speed

k_1 = constant which includes the geometrical constant, gravitational constant, etc.

f = circuit frequency

f_d = rotational speed of the meter disk

k_f = frictional constant for the disk

F_0 = friction constant

During the interval of transition from one load value to another, the torque equation must contain another term. This term, which may be called the transition torque, may be a driving or a retarding torque and will be of sufficient magnitude to balance the torque equation at every instant. The transition torque will be a retarding torque during an increase in load and a driving torque during a decrease in load. The rate of change of the transition torque during a transition interval will depend upon the changes in the other components in the torque equation. Since the retarding torques are a function of disk speed and the meter registration is $\int f_d dt$, the meter registration for loads which are for the most part transitory in nature, will depend on the effect of the transition torque.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Induction-Motor Characteristics at High Slip

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The practical work of inventing the polyphase induction motor, by Nikola Tesla and Galileo Ferraris, was followed by farseeing analytical studies of motor operation. Masterly theoretical analyses of the induction-motor circuit were made by B. A. Behrend, Alexander Heyland, and others. These men, through their insight and understanding, were able to devise ingenious methods for theoretically predetermining operating characteristics of induction motors by employing readily determined constants. For many years these methods of predetermination were accepted and used in practical work. However, as knowledge has expanded and a higher degree of accuracy becomes requisite, it has been found that the older methods of analysis produce inaccuracies which are too great for modern requirements. The trend away from the older methods is clearly shown by abandonment of the use of the classical "circle diagram" in cases where highly accurate results are desired. The use of the former methods of predetermination results in inaccuracies due to several factors, the most important being: (*a*) unjustified treatment of the exciting current, (*b*) the assumption that circuit parameters are constant when they are not, and (*c*) failure to consider the stray load loss. The errors resulting from wrong assumptions may not prove serious for light loading of the motor, but discrepancies increase as load and slip become greater.

A study is made in this paper of the factors which produce rotor losses and corresponding torque in induction motors. A method of accurately analyzing this problem is given, based upon elemental principles and including important effects which have been omitted from previous studies. In order that correct principles may be applied and accurate results obtained in practical determinations, a complete test procedure with required calculations is outlined. The principles developed are illustrated by tests on a selected motor. However, these principles are general in nature and are not limited in their application by the type or size of induction motor. In approach and general treatment of the subject the analysis differs from previously accepted methods. This difference is pronounced in two important respects. In the first place, the analysis gives consideration to the effects of stray load loss. In order to predict results the laws of variation of this loss are investigated and it is shown that it varies as the square of both current and motor speed. The fact that this loss plays a highly important part in the production of motor torque at all higher values of slip is made clearly evident. Secondly, a study is made of the rotor-resistance loss, showing that variations in the value of rotor resistance become a most important factor in such considerations. In this connection, the rotor effective resistance is studied and its variation with the frequency of the rotor circuit is determined. The manner in which the resulting loss operates to produce motor torque is shown clearly by the analysis. Finally, the net over-all torque is derived by combining the separate components. The results show great discrepancies when compared with conventional values.

Investigation of induction-motor characteristics was made over a range of slip extending from zero up to a value of 200 per cent. Accurate determinations show that the actual torque of a motor at high slip may have a value of two or three times that calculated by conventional methods. Discrepancies of this nature have been noted by other investigators[1] and are of such magnitude as to demand

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1. For all numbered references, see list at end of paper.

attention. In modern applications a motor may be reversed by plugging, at which instant the slip is 200 per cent. In such reversing cycles both the heating of the motor and the torque developed throughout the cycle become important considerations. The extent of the heating is determined by the magnitude of the losses and the time required to reverse the motor, the latter depending upon the torque developed. The magnitude of instantaneous torque also becomes an important factor in shaft design. In addition, the results of the investigations with which this paper is concerned have a direct application in problems of polyphase unbalance. In applying the symmetrical-component method of analysis, the action of the negative-sequence current is made truly predictable through the application of the principles herein deduced.

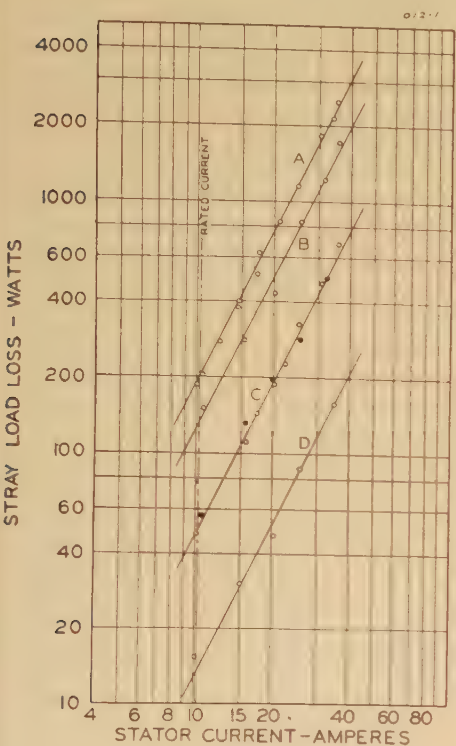


Figure 1. Curves of stray load loss as a function of stator current for different rotor speeds

Curve	Rotor Speed in Per Cent of Synchronous Speed	Rotor Frequency (Cycles Per Second)
A	100	120
B	80	108
C	50	30 and 90
D	25	75

Experimental Investigation

In order to make a practical study of motor characteristics, tests were made on an ordinary squirrel-cage induction motor. To insure that the effects of stray load loss would not show themselves in undue proportion, a motor was selected in which this loss was reasonably low, being 2.08 per cent of full-load input at rating. It was fortunate that considerable test information was already available, this motor having been used in previous tests.[3,4] The motor was rated at ten horsepower, 550 volts, 10.3 amperes, three phase, 60 cycles, and 1,750 rpm. The stator had 48 teeth with semiclosed slots, and the rotor 57 teeth with coffin-shaped slots.

The motor was directly connected to a calibrated d-c machine by a flexible coupling. Power from a three-phase a-c source, having balanced voltage which could be adjusted to any required value, was applied to the stator. Instruments were so arranged that both electrical power input and output could be accurately measured. Measurements were taken at several values of current while the speed was held constant and observed by the use of a stroboscope. Motor current was adjusted to any desired value by control of the applied three-phase voltage. Measurements were made over a range extending from rated current to between three and four times this value. The stator resistance was measured by a resistance bridge immediately following each run, and the friction and windage loss of the two coupled machines was measured at the same time by driving through the d-c machine. Complete runs were made for speeds of 100, 80, 50, and 25 per cent of synchronous speed in the reverse direction to the stator field, for zero speed with locked rotor, and for 25, 50, and 80 per cent of synchronous speed in the same direction as the stator field.

Stray Load Losses

For all points at synchronous speed in the reverse direction values of stray load loss were calculated by the reverse-rotation method.[4] Each point was obtained by taking the difference between the net mechanical power input to the rotor and the net electrical power input to the rotor received from the stator. The results are shown by curve *A* of figure 1 where the loss is plotted as a function of stator current on logarithmic cross-section paper. Curves *B*, *C*, and *D* in this figure show the stray load loss for speeds of 80, 50, and 25 per cent of synchronous speed respectively. The three latter curves are obtained in the same manner as curve *A* except that care is taken to subtract the appropriate value of net rotor power supplied by the stator for each speed. These amounts are 0.8, 0.5, and 0.25 times the rotor power received from the stator for corresponding speeds.

The black points of curve *C* were obtained by operation of the machine at 0.5 speed in the same direction as the stator field (that is, for ordinary motor action). In this case the stray load loss is obtained by subtracting the measured value of net mechanical power developed from one-half of the rotor power received from the stator. The close agreement between values obtained in this manner with those obtained from reverse rotation at the same rotor speed indicates the degree of accuracy of the reverse-rotation method at this particular speed. This substantiates the assumption that the stray load loss is not affected by the direction of rotation.

Curves *A*, *B*, *C*, and *D* of figure 1 all have a slope of two indicating that the stray load loss varies as the square of the current for all values of speed.

In order to determine the law of variation of stray load loss as a function of motor speed, values of the loss at different speeds were taken from the curves of figure 1 at the point of rated current. In figure 2 these quantities are plotted as a function of motor speed on logarithmic cross-section paper. The fact that the resulting curve has a slope of two indicates that the stray load loss varies as the square of the rotor speed for constant current.

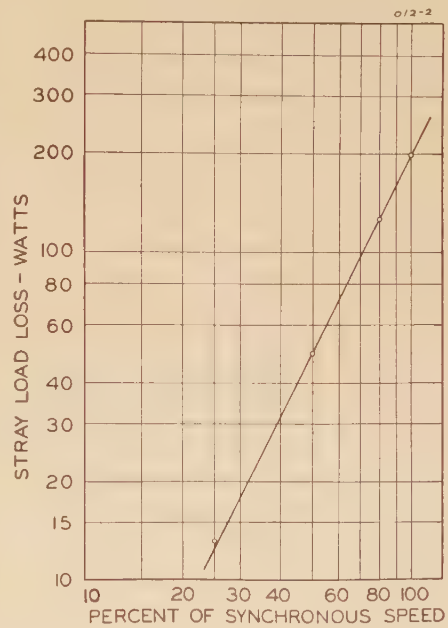


Figure 2. Stray load loss as a function of speed at rated current

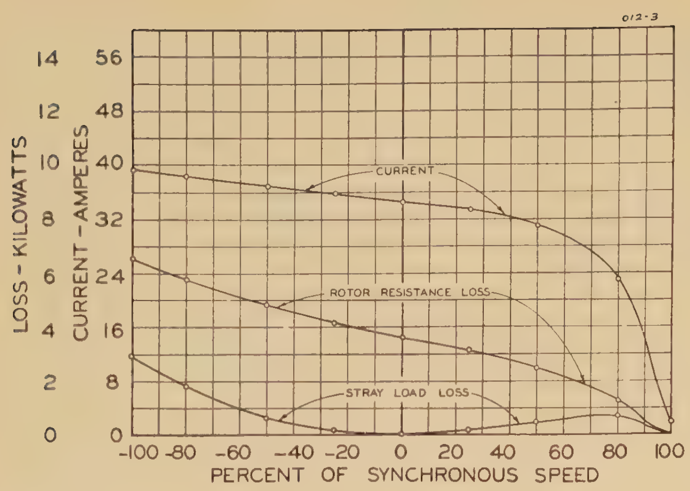


Figure 3. Stator current and losses at one half voltage as function of rotor speed

Motor Characteristics at One-Half Voltage

Since it was impossible to obtain measurements at full voltage for the speeds selected without damaging the motor due to overheating, the characteristics of the motor were first obtained at one-half rated voltage. The top curve of figure 3 shows measured stator current as a function of rotor speed for this value of constant applied voltage. The bottom curve gives stray load loss for corresponding speeds and currents as determined from figure 1. This loss is produced by rotation of the motor and consequently becomes zero at the point of zero speed. Being a tooth-frequency loss it is the same for a given speed and current, irrespective of the direction of rotation.

The rotor resistance loss was determined as the product of slip and air-gap power, the air-gap power being taken as stator input less stator copper and iron losses. In addition the rotor resistance loss was also calculated from the measured shaft power. In this latter case for rotation in the positive direction, the sum of shaft-power output, friction and windage loss, and stray load loss was divided by (1 — slip) to obtain the air-gap power. For rotation in the reverse direction the sum of friction and windage and stray load loss was subtracted from the mechanical power input to the shaft and the difference divided by (slip — 1) for obtaining air-gap power. The fact that the values of the rotor resistance loss obtained from the stator electrical power input and from the mechanical shaft power showed good average agreement indicated that the iron loss due to the stator leakage flux was of negligible importance for these calculations.

The rotor resistance loss thus obtained is of the nature of an *effective* resistance loss and includes all components of loss that occur as a result of the slip-frequency rotor currents. In addition to the slip-frequency copper loss component, there may be components of eddy-current losses in the rotor circuit and slip-frequency iron losses caused by the air-gap and rotor-leakage fluxes. This effective resistance loss of the rotor is shown by the middle curve of figure 3.

Each loss produces its own value of torque. The rotor effective resistance loss results in a force from the reaction of slip-frequency currents in the rotor and the air-gap field rotating at synchronous speed. Thus the torque can be calculated from the power loss and the difference in speed of the rotor and the synchronous field (that is, the slip speed). The dashed-line curve of figure 4 shows the torque resulting from the rotor effective resistance loss. At small values of slip a small loss produces a large torque while at high slip it takes a large loss to produce the same torque. The torque resulting from the rotor resistance loss is the only component of torque which in the past has been considered in conventional calculations. The curve of rotor resistance loss shown in figure 3, and corresponding torque of figure 4 differ from customary calculations in that they are derived from actual measurements, instead of being calculated from a value of rotor resistance which is usually considered as constant.

The stray load loss produces a drag on the rotor which in this respect is similar to friction and windage effects. Thus the torque resulting from it has a negative value over the complete range of positive directional speeds, reducing the available torque of the motor. However, during reverse rotation the torque from this loss tends to stop the motor, thus operating in the same direction as the torque from the rotor resistance loss. Consequently both quantities are considered as positive over this range of speeds. The torque resulting from stray load loss is shown by the bottom curve of figure 4. It is important to note that the stray-load-loss torque occurs at the speed of the rotor. While this loss (as shown in figure 3) does not appear large it may produce a relatively larger torque. If for example we consider relative values at the point of synchronous speed in reverse direction, we find the stray load loss is less than one-half the value of rotor resistance loss. However, while the stray load loss results from forces occurring at the rotor speed, the rotor resistance loss is produced by reaction with the stator field which is moving at double synchronous speed with respect to the rotor. Since the torque for any rotor loss varies inversely as the speed of the force reaction producing it, the difference in speed results in torque from the stray load loss which is nearly equal to that from the rotor resistance loss at this point.

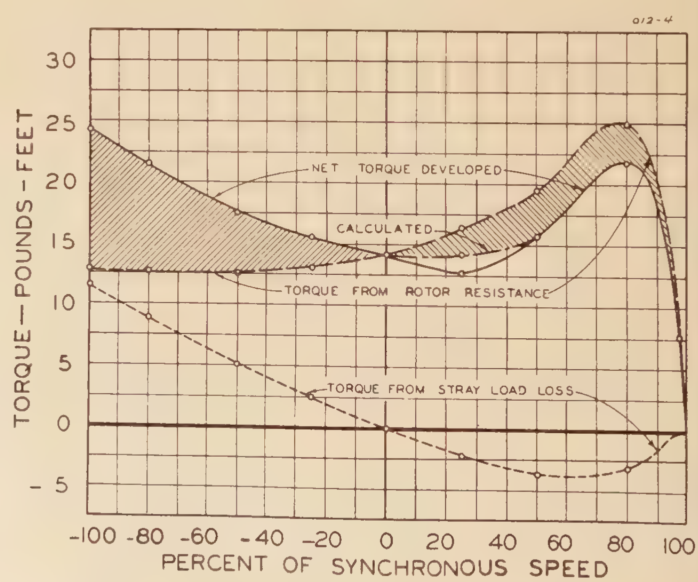


Figure 4. Torque curves for one-half-voltage operation

The combination of the torque from stray load loss with that from the rotor resistance loss gives the net torque available to drive the rotor. Stray load loss causes a reduction in torque over the range of direct rotation which is shown by the shaded portion to the right of the point of zero speed in figure 4. For reverse-rotation operation the torque from stray load loss causes a marked increase in the net torque tending to stop or reverse the motor. This effect is shown by the shaded portion at the left of the diagram. It is significant that the measured shaft torque, after being corrected for friction and windage, gives a net value which is in complete agreement with the resultant of the two components, with the exception of a short portion of the curve between zero and one-half speed in the positive direction. The discrepancy over this range is considered to be the result of torque effects caused by harmonic components of flux. The full-line curve marked "net torque developed" in figure 4 was obtained from measured output.

Rotor Effective Resistance

All losses which occur at slip frequency in the rotor have been considered as rotor *effective* resistance loss. This loss was found to vary as the square of the current for a given frequency but to have different values for the same current at different frequencies. This indicates that the effective resistance of the rotor is not constant. Its value for one phase of an equivalent wye-connected rotor was obtained by dividing the total loss by three times the square of the rotor current. The equivalent effective resistance for each phase of the rotor circuit is shown by the curve of figure 5. Since the total loss includes among its components hysteresis and eddy-current iron losses due to the rotor leakage flux, it could not be expected that the effective resistance would remain constant at different rotor frequencies.

The curve shows that the rotor re-

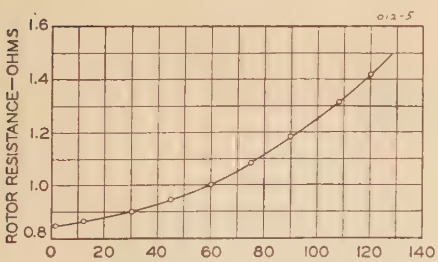
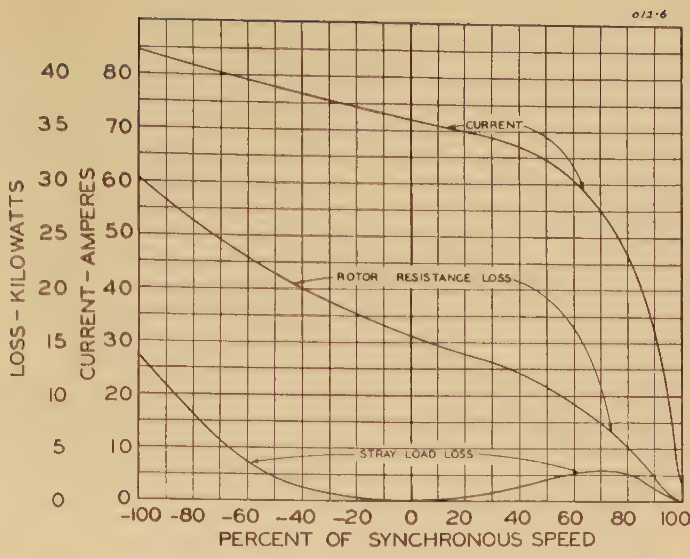


Figure 5. Curve of rotor resistance per phase as a function of frequency in the rotor circuit

Figure 6. Curves of current and losses at full voltage



sistance increases appreciably at higher frequencies, being about 1.68 times as large at 120 cycles (synchronous speed in reverse direction) as it is at very low frequencies. At zero speed (locked rotor) the resistance has risen to 1.18 times its lowest value.

It was found that the resistance could be expressed by a mathematical equation of the following general form

$$R_{\text{eff}} = a + b\epsilon^{mf}$$

where R_{eff} is rotor effective resistance in ohms per phase, f is frequency in cycles per second, ϵ is the base of natural logarithms, and a, b, and m are constants. Supplying values of the constants for this particular case gave the equation

$$R_{\text{eff}} = 0.74 + 0.103\epsilon^{0.0158f}$$

Characteristics at Full Voltage

Knowing the value of rotor effective resistance and the laws of variation of stray load loss with current and frequency, motor characteristics at full voltage can be easily calculated if current values can be determined. The latter were obtained by extrapolation of current-voltage curves taken at constant speed. A slight curvature in such curves, extending up to a point of approximately twice rated current, indicated small effects due to tooth saturation. For higher values of current the curves become straight lines permitting accurate extension to the point of rated voltage. Current values obtained in this way are shown by the top curve of figure 6. The rotor resistance loss then was calculated using values taken from figure 5, and the stray load loss was obtained by extrapolation of curves of figure 1. The resultant loss curves are also shown in figure 6.

Torque values corresponding to each of the losses were obtained in the manner previously described for the one-half voltage characteristics. The resultant net torque curve was then found by combining the torque components as in figure 4. This net torque developed at full voltage is shown by the full-line curve of figure 7. Stray load loss has a more pronounced effect in altering the torque curve at full voltage than at one-half voltage due to the fact that this loss and its corresponding torque vary as the square of the current. The full-voltage torque curve is obtained on the assumption that both rotor and stator resistance remain unchanged from heating by the high currents, which would not be the case if such currents were maintained for more than a very short period. This torque curve is quite accurate except over the range of motoring speeds extending from zero to approximately one-half synchronous speed. Over this range harmonic fluxes may cause changes in torque which are difficult to predict.

In order that this speed-torque characteristic might be compared with the curves calculated in the conventional way from constants measured under locked-rotor conditions the latter are also given. The dotted-line curve marked "theoretical—A" is derived from circuit parameters measured at zero speed with current corresponding to the point of rated voltage. Consequently it agrees with the actual curve at this point. The dashed-line curve labeled "theoretical—B" is computed from locked-rotor circuit parameters taken at the point of rated current. The rotor effective resistance was the same for these two cases, but the combined leakage reactance was larger for the case of rated current. This latter difference was due to magnetic saturation

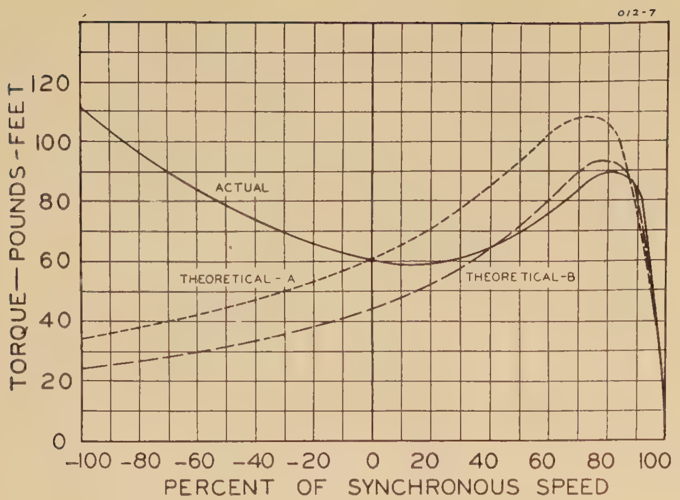


Figure 7. Comparison of actual torque to be expected with torque curves computed from locked-rotor measurements

in the path of the leakage flux as above mentioned. This difference in value of leakage reactance produces very different theoretically computed speed-torque curves. However, the important fact to note is the pronounced difference between the actual torque and that obtained by calculations from locked-rotor data. At synchronous speed in the reverse direction the actual torque developed is more than three times that computed by conventional methods.

A New Accurate Method

The ability to obtain accurate characteristics of induction motors without actually measuring them is most desirable. It is evident that if such predetermination is to be made it will require more information than can be obtained from locked-rotor and no-load tests. The effects of stray load loss and the variation of rotor effective resistance as a result of change in rotor frequency must be taken into consideration. These effects may be included readily by adopting the following procedure.

In addition to the customary locked-rotor and no-load tests two additional tests become necessary. These are a reverse-rotation test and an ordinary load run. The reverse-rotation test has been fully specified in a previous paper[4] which should be referred to for a complete description. This test, which is made at synchronous speed in reverse direction, should include data over the range of current from rated value up to as high an amount as can safely be used without overheating the machine. The test will give stray load loss as a function of current at synchronous speed. By application of the law that this loss varies as the square of current and speed its value can be calculated for any required condition. The rotor effective resistance loss can be readily obtained by taking twice the air-gap power for points of test. Knowing the resistance loss for given values of current the rotor effective resistance can be calculated readily at double frequency. A current-voltage curve can also be plotted, which when extended as a straight line above the point of saturation will give the current for rated voltage.

The locked-rotor test would be made as in the past over as large a range of current as possible. The results should be shown in a current-voltage curve which may be extended as above to the point of rated voltage. Impedance per phase can be calculated from voltage and current at this point. Then by using the average value of input effective resistance a value for total inductive reactance can be obtained. Measurement of stator resistance will permit determination of the rotor resistance by separation.

An ordinary load run should be made in which the slip is measured with high accuracy. Output power is not an important measurement as air-gap power can be obtained by subtracting stator copper and iron losses from measured input power. Multiplication of air-gap power by slip will give the rotor resistance losses. Rotor current is found by vector subtraction of the exciting component from the stator current. Rotor resistance per phase is then computed from rotor losses and rotor current.

We now have three points of rotor effective resistance, that is, points at low rotor frequency, locked rotor, and double frequency. This will permit the drawing of a curve of rotor resistance similar to that of figure 5. It now remains only to find current values for rated voltage in order to determine rotor resistance loss and stray load loss. Current at no load and at rated load has been obtained by measurement. Also, values of current are available for the locked-rotor point and for that of synchronous speed in reverse direction. This leaves points of current between that of zero speed and full load to be determined. Values of rotor resistance over this range are available from the curve. By assuming values of slip and dividing the corresponding rotor resistance by it we obtain the equivalent circuit secondary resistance. The total input resistance is obtained by addition of primary resistance to secondary equivalent resistance. This may be combined with the input reactance obtained from the locked-rotor test to find the total input impedance. It has been found that leakage reactance remains nearly constant over this range of speeds, but any slight variation therein is not serious because of the greater importance of the rotor equivalent resistance. Knowing the equivalent impedance, current values can then be calculated for any given speed. As the current curve appears to be almost a straight line between zero speed and synchronous speed in reverse the complete current curve can now be drawn. Loss curves can be determined and corresponding torque curves obtained. Resultant torque is then found by combination of the component values. The experimental work necessary to obtain accurate determinations as above described is not increased greatly over that required for conventional determinations, the main additions being the reverse-rotation test and the measurement of slip for a corresponding value of power input under load. Calculations are simple and straightforward with the separate steps following in a logical manner.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Control of Inductive Interference to Telegraph Systems

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FELLOW AIEE

THE tendency of power-supply and distribution systems to cause extraneous currents to flow by induction into telegraph lines has presented a diversity of problems which are of concern to both interests. No one solution is found to be of general application; rather it ordinarily is necessary that each situation be made the subject of individual study.

In different instances it may be most economical to control the interference by attention to the design of the power system, or by choice of routes for each line, or by mitigative equipment applied directly to the telegraph system. The present paper will be limited in scope to the third class of control methods; it will describe various special devices which may be applied in different cases to the telegraph circuit for reducing the power interference, with indications of their accomplishments and of their limitations.

The discussion herein is in particular reference to interference which tends to continue during normal working of the power systems, although some of the devices referred to are also effective in removing those more severe surges which occur at times of power line or equipment failures. Extraneous voltages are induced where power and telegraph lines parallel, and tend to reduce the capacity and the dependability of the telegraph. An exposure one mile in length at a separation of a few hundred feet may result in a small or a severe interference dependent upon the nature of the power system and type of telegraph circuits. The voltages are caused by the magnetic field created by the power system, which interlinks the telegraph wires. The electric field from the power line is seldom of importance.

Usually the fundamental frequency of the power system, 25, 50, or 60 cycles, is of chief concern. Sometimes the third harmonics of these create interference. In our experience no cases have occurred where harmonics higher than the third have created interference to physical telegraph circuits. The interference is most severe where some part of the power current flows in the earth, as may be the case when neutral points are grounded, or as always occurs in electric-railway practice.

As distinct from power practice the telegraph circuits ordinarily are not worked at any standardized frequencies. The assigned speed of each telegraph depends upon the amount of business between the terminuses; economical considerations require that where the business is sufficient to justify, the speed shall be the maximum practical working capacity of the line between the points.

The consideration that in this country there are many situations where large volumes of telegraph business exist between cities widely separated, has created a strong incentive to develop the maximum telegraph line speeds. As part of this objective Western Union has endeavored to survey every practical method for minimizing the effects of power induction.

Review of Theory of Telegraph Transmission

The transmission of intelligence by telegraph requires that current, controlled in accordance with a code and representing the message to be sent, shall be impressed on the line and shall be correctly interpreted at the distant end of the line. The discussion herein will be in particular reference to the multiplex printing telegraph system, which serves for the more important message circuits and which utilizes probably the most efficient available code. However, the fundamental problems of line transmission are the same in all telegraph systems.

In the multiplex each letter or figure is represented by a code character consisting of five units of time. During each time unit there is applied to the line either positive or negative battery as indicated in figure 1, the battery ordinarily being of 160 volts. No space occurs between consecutive characters. A measure of the speed of the circuit is the "dot frequency" or the "fundamental signaling frequency" of the circuit, which is the reciprocal of the time required for two consecutive units in the code character.

During its passage along the line the telegraph signal becomes rounded and the current becomes weakened. The practical working circuit speed is limited by the amount of weakening of the signal which can be tolerated in the presence of such extraneous currents as then exist. Any induced currents from external sources are of course superposed on the received telegraph current, and amounts of induction exceeding about six volts are sufficient to cause a measurable impairment of the telegraph.

In field measurements of telegraph transmission it is customary to examine the current sent and received, and the rate of change of the current between reversals. However, for analytical purposes it often is useful to regard the circuit as an a-c transmission system. While telegraph transmission would appear superficially to be wholly different in principle from that of power supply, there is only this basic difference, that while the power supply system need transmit one frequency only, the telegraph circuit must be capable of sending a band of frequencies the lower limit of which is zero frequency and the upper limit of which is somewhat above the dot frequency.

If in the telegraph transmitter a given combination of signals is set up and is

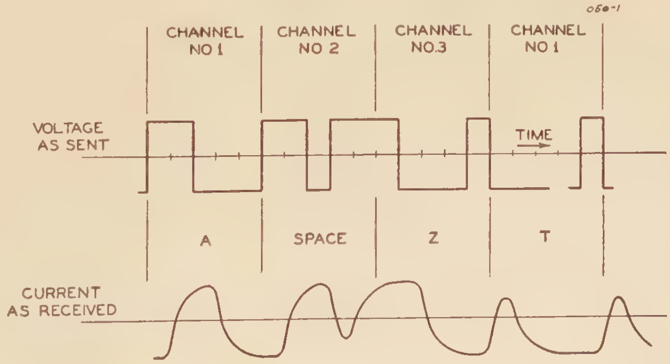

Figure 1. Typical signals in three-channel multiplex printing telegraph system

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repeated over and over, the combination may be analyzed by well-known methods into the sum of a number of sinusoidal waves of definite frequencies. In figure 2 are shown the frequencies contained in certain signal combinations when repeated again and again. Values above 200 cycles are not shown, although actually they continue with decreasing amplitude to infinite frequency.

Commercial telegraph traffic, of course, is made up of random reversals of voltage

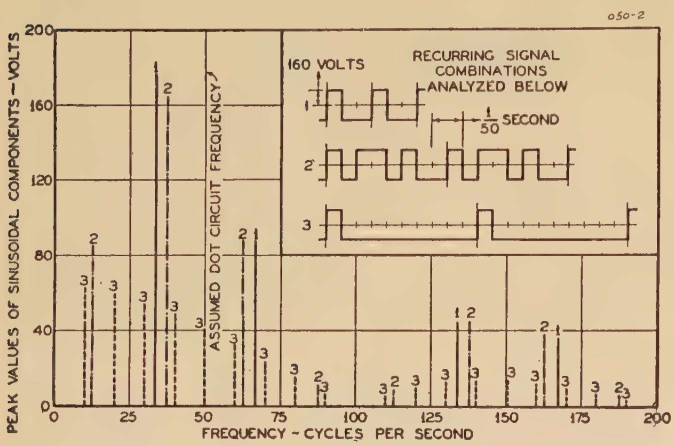


Figure 2. Examples of analyses of repeated telegraph signals into their sinusoidal components

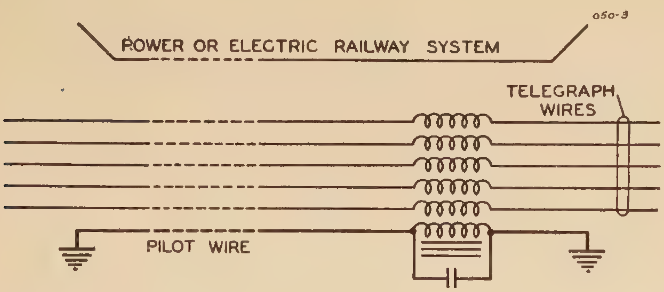


Figure 3. Multiwire neutralizing transformer

rather than of recurring signal combinations. In strictly random traffic the frequency spectrum is found to be continuous, that is, it contains substantially *all* frequencies from zero upwards, rather than certain discrete frequencies.

If the telegraph circuit were to transmit all frequencies without reduction in amplitude and in correct phase, the received signal would be identical to that sent. In practice the upper frequencies are reduced or removed in traversing the line, and the effect on received signal shape is to cause the rounding previously referred to. A certain degree of such rounding is not objectionable and may be desirable. In practice it is found that frequencies above about 1.6 times the dot frequency are not essential in the received signal, although some advantage is gained if harmonics up to the third or even the fifth are present. Any material alteration of those frequencies which are in the useful or essential range tends to cause distortion or mutilation of the received signals.

Devices for Separating Power Induced Voltages From Telegraph

Once extraneous voltages have been induced from a power system into telegraph, their removal is difficult only because of the need for minimizing any direct impairment to the telegraph. Equipment for removing the interference must not introduce any material added impedance into the telegraph nor remove any essential components of the telegraph currents, otherwise its objective is defeated. Among telegraph circuits carried along a common route there ordinarily is some tendency to induce currents known as "cross fire" into each other; the equipment for removing power interference must not increase such cross fire.

Interference of course can be removed by replacing the customary ground-return telegraph circuit by a metallic telegraph, using two line wires instead of one. Or a carrier telegraph may be substituted. Placing the wires in cable, particularly if armored, is effective for the purpose and also affords mechanical protection, but is expensive. An increase in the voltage of the telegraph battery helps to a small extent in overriding induced voltages. Such arrangements occasionally may be justified to reduce power interference, but hardly can be considered to be a general solution as a co-ordinative measure.

Devices for removal of induced power voltages are of two general classes. In the first a pilot wire set aside for the correction, is placed on the pole line carrying the telegraph wires and extends throughout the length of the exposure to power. The second class of devices depends upon tuning to remove the sinusoidal power current.

Mitigative Systems Including a Pilot Wire

The pilot wire is exposed to the same induced voltage as the telegraph wires. This is conducted by the pilot wire into suitable equipment which in turn applies to the telegraph wires a voltage to neutralize the interference.

Neutralizing Transformer

Illustrated in figure 3, this is a relatively simple device which under suitable conditions is fairly effective. In one form it was used early by Professor C. F. Scott. All wires on the pole line may be corrected simultaneously, all transformer coils in the multiwire transformer being wound on the same iron core.

As at present developed the step-up ratio is only slightly above unity, and the inductance of the primary winding is tuned to the disturbing frequency. To prevent partial saturation of the core by currents in the telegraph wires, an air gap is included in the core. The correction of voltages up to 200 in an exposure 20 miles in length, has been obtained with a transformer weighing 500 pounds, in as many as 34 wires carried on the same pole line. The removal of power interference is nearly perfect unless limited by conditions such as local earth potentials at the grounding points, but the system tends to add cross fire between the various telegraph circuits.

As in all other correcting systems it is necessary to examine the direct effect of the transformer on the telegraph currents. The transformer adds impedance in each telegraph wire, but more important is the cross fire induced between

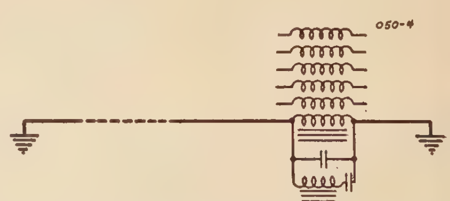


Figure 4. Neutralizing transformer for correction of two frequencies

the various wires. These effects may be controlled by holding to a low value the resistance of the primary circuit. That is, a mutual impedance exists between each pair of telegraph circuits, which may be considered to consist of an inductance shunted by the capacitor and by the primary circuit. The resistance of the latter including the wire and its earth connections should not exceed 40 ohms and preferably should be lower. To this end there have been used pilot wires as large as number 3 Brown and Sharpe gauge, with earth connections made of a dozen paralleling grounding pipes. The limitation in resistance obviously sets a limit on the length of exposure in which a multiwire neutralizing transformer can be used economically, where high-speed telegraph circuits operate.

If the telegraph circuits are worked at low speed, or if a separate pilot wire is provided for each telegraph circuit, the limitation as to length becomes less difficult. Individual line neutralizing transformers have been used in exposures up to 60 miles in length using a pilot wire of number 9 Brown and Sharpe gauge in a relatively low-speed telegraph circuit, for correction of 25-cycle interference.

The neutralizing transformer may be used for simultaneous correction of several frequencies. An arrangement in service for removing 25- and 75-cycle interference is shown in figure 4, and includes, in addition to the transformer, a second capacitor and an added reactor.

The above transformers were designed for use during normal working of the disturbing power or railway system. A unique application has been made in a five-mile exposure of an electrified railway to circuits of a burglar-alarm system, where frequent railway short circuits caused false alarms by induction. In this case the induction reached values over 100 volts which were interrupted in about one cycle through the operation of railway circuit breakers. A transformer was provided which could adjust itself sufficiently quickly to correct the transient voltage, by tuning to 25 and 50 cycles through the use of two coil-capacitor units shunting the primary coil, and was effective in neutralizing the abrupt severe surges of voltage.

Neutralizing Generator

The neutralizing generator formerly has been in service use but is now superseded by the system next to be described. It will be discussed briefly because of the light it throws on the general problem.

Various arrangements of this have been developed, of which one is shown in figure 5. A multiwire transformer is energized by means of an a-c generator, and counterbalances the induced voltages both in telegraph wires and in the pilot wire. Any residual voltage in the latter is rectified in a mechanical rectifier driven synchronously with the generator, and after amplification serves to correct the voltage of the generator and the speed of the driving motor until the correct compensation is effected.

The system is effective in correcting interference, but is sluggish in adjusting itself when changes occur in the induced voltage. All a-c components of the telegraph signals must flow through the generator armature, and in order to minimize the addition of impedance in the telegraph wires and the tendency to cause cross fire between them, the impedance of the armature must be held to a low value. The pilot wire may be of the wire size ordinarily used for telegraphy, and the system is practical for exposures much longer than is the multiwire neutralizing system previously described.

Neutralizing Amplifying System

This system is probably the most valuable of those available. It has made it possible to maintain practically normal operation in over 260 telegraph wires which are exposed to interference at 25 cycles from the electrified zone of a large eastern railroad, where voltages approaching 200 volts are induced. The system is also in use elsewhere for correcting interference at 60 cycles.

The neutralizing amplifying system is illustrated in figures 6 and 7. As with systems previously described, a transformer serves to impress on each telegraph wire a voltage to counteract the disturbing voltage induced in line wires. In this case the transformer is energized by a vacuum-tube amplifier. The voltage induced in the pilot wire is also opposed by the voltage in one coil of the transformer, and the residual is impressed upon the amplifier. The ratio of the potentiometer is not the same as the turns ratio of the opposing coil with respect to the line coils. Through adjustment of each of these ratios it is possible to obtain a step-up action which provides neutralization approaching 97 per cent. Since the system is aperiodic, it is able to neutralize sudden surges of voltage such as caused by power-system short circuits, as well as continuous interference within the voltage limitations of the equipment.

The manner of providing for the passage of the useful telegraph currents is unique. It might appear that the arrangement would impress a high impedance upon the telegraph currents, and would tend to add cross fire between circuits. The circuit, however, is such that a current is caused to flow in the transformer coil in the output of the amplifier, which (corrected for turns ratio) is equal to the sum of the telegraph currents in all line coils, thus cancelling any flux in the transformer due to telegraph currents. If the current in the output coil departs from the amount to

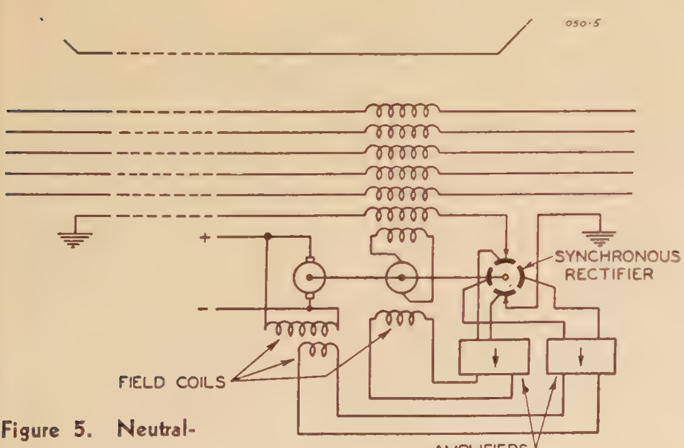


Figure 5. Neutralizing generator

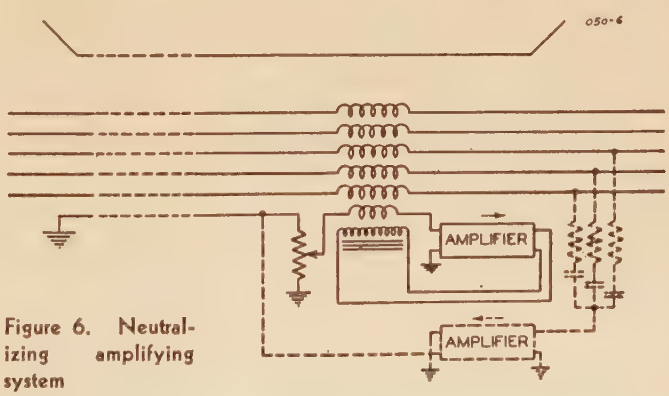


Figure 6. Neutralizing amplifying system

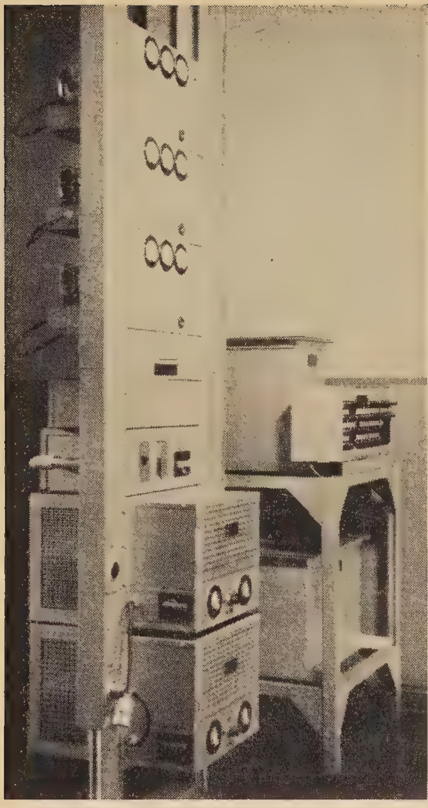


Figure 7. Neutralizing amplifying system for correction of 150 volts at 25 cycles in 60 telegraph wires

balance the telegraph currents, a residual voltage is immediately impressed upon the input of the amplifier tending to correct that condition.

A complication occurs in connection with the cross fire which normally occurs between telegraph wires carried on a given pole line. If the cross fire between all circuits including the pilot wire were equal, this system would also be effective in reducing the cross fire. Actually it is impracticable to locate the pilot wire in a manner to prevent its being affected by enhanced cross fire from a few wires, and unless compensated that cross fire would interfere with the operation of the system as a whole. Where high-speed telegraph circuits are present a correction for this crossfire condition is necessary and is shown in dotted lines in the figure.

With one set of the neutralizing equipment as shown, a limitation exists in the distance that the exposure may extend from the equipment, because of phase changes along the wire. The efficiency tends to decrease where the distance exceeds 20 miles in the case of 60-cycle interference, or where it exceeds 40 miles with 25-cycle interference. These distances are reduced if the telegraph wires are in cable. These limitations are removed by utilizing two sets of equipment, one at or beyond each end of the exposure, in which case the pilot wire may be 200 miles or more in length.

An arrangement somewhat similar in principle to the one illustrated was first shown by H. M. Trueblood of the Bell Telephone Laboratories. In its present form the system was developed here by W. D. Cannon.

Mitigative Systems Dependent Upon Tuning

Many combinations of reactors and capacitors have been proposed with the view to reducing or removing extraneous sinusoidal currents by tuning. The expense of a pilot wire is thus avoided. The tuning removes those same frequencies from the useful telegraph currents and thus may impair the operation of the telegraph circuit by an amount dependent upon the relative frequency of the telegraph and the interfering frequencies, and upon the breadth of the tuning. A description of a small number of tuned devices will suffice to illustrate their practical value in mitigating interference.

Resonant Shunts and Resonant Chokes

A simple resonant shunt or choke, as shown in figures 8*A* and 8*B*, was introduced early for removal of interference. It may remove 95 per cent of the interference, but because of its coincident removal of useful telegraph currents it can be used only where the dot telegraph frequency is less than about half of the interfering frequency. This greatly restricts its use in modern systems of telegraphy. The effectiveness of the coil increases with its size; the above statements are based upon the use of an inductor weighing 20 pounds.

While simple resonant devices cannot be used for removal of 25- or 60-cycle interference from high-speed telegraph circuits, the resonant shunts are effective in such circuits where the interference results from power harmonics at 180 cycles. For application where conditions permit, the resonant shunt is placed in parallel with the working telegraph relay. The resonant choke is convenient for use in "way" telegraph circuits where a number of stations operate on the same line, since one choke may serve where several of the resonant shunts would be required.

Balanced Double-Resonant Network

A balanced arrangement shown in figure 8*C* was proposed by E. Blakeney and R. E. Chetwood, which in theory may remove all of the interference. The resistor is adjusted to equal the a-c resistance of the coil and capacitor at resonance. Advantage may be taken of the arrangement to increase the value of the inductance and reduce the amount of capacitance, with the result that the impairment to the telegraph is much reduced.

That arrangement has been little used, but a development from the same principle is the balanced double-resonant network shown in figure 9. The theory of this is rather involved, but it may be considered that the a-c resistance of a double-resonant shunt is balanced against that of the resonant choke combination in a manner to remove nearly all interference. Partly through the circuit design and

Figure 8. Resonant devices for reducing interference

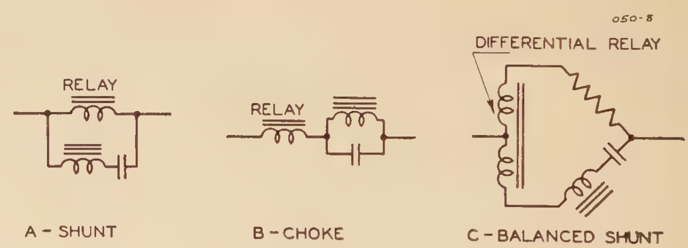
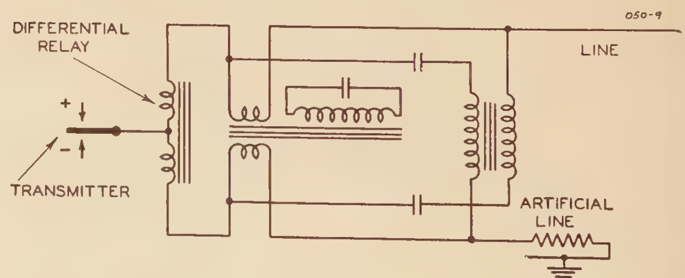


Figure 9. Balanced double-resonant network



partly through an increase in the weight and effectiveness of the inductors, a much improved performance results. Each inductor is designed to offer the highest ratio of reactance-to-resistance obtainable within practicable size limits. The cores are of silicon steel and contain air gaps. This device is wholly practical, and with some moderate impairment of the telegraph currents it may be used where the telegraph dot frequency approaches nine-tenths of the interfering power frequency. Typical plots showing the efficiencies of various tuned devices in removing interference are shown in figure 10.

The effectiveness of the balanced double-resonant network is dependent upon the power frequency remaining nearly constant. Failures of the device in removing interference have occurred because of variations in the frequency of the disturbing power system.

Synchronous Selective Neutralizing System

The arrangement just described provides nearly the practical limit of sharpness of tuning which may be secured with direct use of coil-capacitor tuning. It is possible to obtain selectivity many times closer through the use of mechanical tuning, or by an arrangement which involves rectification, a delay network, and reconversion to alternating current. A system of this type is indicated in figure 11. With such tuning as plotted in figure 10, the amount removed from the telegraph frequency spectrum is so narrow, presuming that random telegraph traffic is transmitted, that the impairment to the telegraph signals is not serious, and the telegraph dot frequency is not limited to values below the disturbing frequency as was the case with other tuned devices.

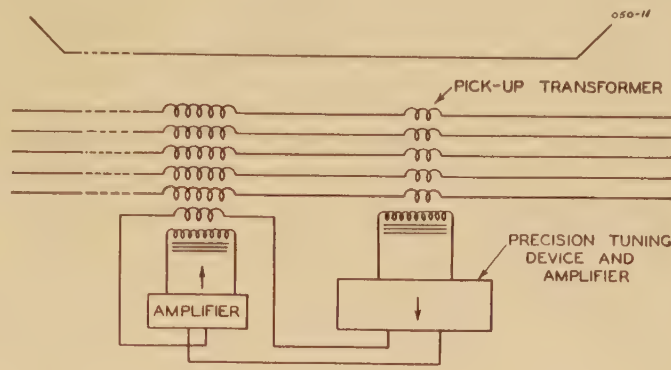


Figure 11. Synchronous selective neutralizing system

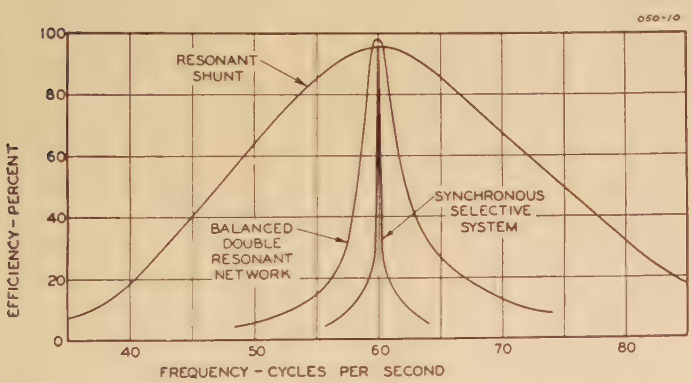


Figure 10. Efficiency of removal of sinusoidal currents by tuned devices

In practice a complication occurs because the telegraph signals are not wholly random. Certain characters, for example the letter "e", the space between words, etc., occur more frequently than others. When one multiplex channel is idle a blank is transmitted repeatedly, and at times circuit testing is done with a recurring set of characters. When telegraph signals containing such combinations are analyzed into their sinusoidal components (see section on telegraph theory) it is found that certain frequencies are more prominent than others and if one of those frequencies should nearly coincide with the interfering frequency there is impairment of signals and possible cross fire between circuits.

The values of those prominent frequencies have been computed by setting up combinations of signals likely to occur. For a two-channel multiplex it is found that the prominent frequencies are given by the formula $nF/5$, where F is the dot telegraph frequency and n takes all integer values from one to infinity. For the three-channel multiplex the formula is $2nF/15$, and in the four-channel multiplex it is $nF/10$. An exception is that frequencies of $2F$, $4F$, $6F$, etc., are not present, and frequencies near those values are of little importance.

There are, therefore, limitations upon the telegraph circuit speeds which can be worked to best advantage on a line where a synchronous selective neutralizing system is in use. A list of the telegraph dot frequencies to be avoided under these circumstances, as determined from the above formulas, where the interference is at 60 cycles, appears in table I.

Provision for passage of the useful telegraph currents is made in the same manner as in the neutralizing amplifying system previously described. The system is of course quite complex, and has the further disadvantage that a time interval of the order of 20 seconds is required for it to readjust itself for changes in amount of induced voltage, this sluggishness being a corollary of the extraordinarily sharp tuning. During that interval the interference remains partly uncorrected. Arrangements are incorporated for automatic adjustment of the frequency of the tuning to follow normal changes in the frequency of the power system. Interference from two unsynchronized power systems cannot be neutralized by a single set of this equipment.

Table I. Telegraph Dot Frequencies Which Conflict With Operation of 60-Cycle Synchronous Selective Neutralizing System

Two-channel multiplex	25.0.....27.3.....33.3 37.5
Three-channel multiplex	37.5.....40.9.....45.0 50.0.....56.2
Four-channel multiplex	50.0.....54.6.....60.0 66.7.....75.0

The values listed include only those which occur within the customary range of operation of the stated equipment.

Discussion and Conclusions

This discussion of methods for mitigating interference obviously has been quite one-sided, since due to limitations of space there has been no discussion of matters of design of the power system which may influence the interference, yet in many cases the best solution will call

for some modification of the plans of the latter. Such matters are dealt with in various other publications. In general those features should receive consideration with every exposure, since the only procedure that can be justified is that in which the greatest total benefit is obtained with a minimum total expenditure.

Many devices have been investigated for application to telegraph circuits for removing interference, and of those the preceding has been limited to descriptions of a small number sufficient to indicate their general range of usefulness. Neutralizing systems embodying a pilot wire through the exposure are effective for all classes of telegraph service, and are most useful where the exposure is short and where many wires can be corrected with one set of equipment. Systems dependent upon tuning are frequently unsuitable because of a greater tendency to cause direct detrimental effects to the telegraph currents, but find application in some circumstances where pilot-wire methods would be uneconomical.

But because of the cost, of the added complexity in telegraph circuits already highly complex, and of the weakening of the useful signaling currents in some cases, there are often objections to the use of such correcting equipment in exposures causing moderate or small amounts of power induction. In each instance there is some minimum value of induced voltage below which the application of neutralizing devices is not justifiable. To the telegraph company the most serious type of exposure is that which creates small interference only—a conclusion which follows from the fact that such exposures are far more numerous than the more severe ones, and their damaging effect upon telegraph service is to some extent additive.

However, the application of neutralizing devices to the telegraph circuits is proper where conditions are such that the creation of an exposure causing material induced voltages is justifiable, and fortunately it is possible to state that through the use of different methods in different cases there have been few exposures which during normal conditions of the power system, are so severe individually as to effect any serious impairment to telegraph service.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Harmonic Theory of Noise in Induction Motors

WAYNE J. MORRILL
MEMBER AIEE

Synopsis: This paper presents a theory of noise generation particularly adapted to use with small motors. Since single-phase motors predominate in the small-motor field, a single-phase point of view has been employed.

The underlying philosophy of the paper is to reduce the theory to simplest terms and to concentrate attention upon the most probable sources of noise. While the results are shown as a large collection of numbers representing force waves the development steps of the theory are really simple and easily understood.

The resultant air-gap flux wave in an induction motor is the difference between the fundamental stator flux plus its harmonics and the fundamental rotor flux plus its harmonics. The difference between the two fundamental fluxes is usually less than the larger one and often less than either one but the harmonics, with few exceptions, are neither of the same velocity nor space order and, therefore, do not add or subtract from each other. It follows that the resultant flux wave has more harmonics of much greater per-unit amplitude than does either the stator or rotor flux wave alone. It is the interaction of two large harmonic flux waves of slightly different space order and traveling at high frequency with respect to each other that causes high-frequency magnetic-force waves of long space pitch which are effective in producing noise.

The theory has been used for some time in noise investigations and has been found to bear out test results on a large number of motors. It is hoped that its presentation will not only prove useful to others but will encourage further contributions to the understanding of noise.

THE present-day problems which confront the designers of electric motors have been to a considerable extent complicated by the necessity for producing motors of greater and greater quietness. Since the pressure of economics precludes the possibility of obtaining quietness by the introduction of massive structures, ways must be found to obtain desired levels of quietness with the same or lighter structures than those previously used.

Paper 40-13, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted October 14, 1938; made available for preprinting December 21, 1939; released for final publication March 8, 1940.

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There have been a number of papers on noise of electrical machinery which have undertaken to deal with the problem of producing quiet motors from a scientific designer point of view. Many of these papers have been unsatisfactory to those engineers who desire always to have a sound and rigorous theory against which to check data, form conclusions, and make predictions. Much of the work which has been presented on noise has been of an experimental nature and has been presented at least semiempirically. Other work has been presented which, experience indicates, appears to be based upon unnecessarily complicated conceptions.

It appears that a sound theory having a simple philosophy and starting from a few simple fundamental assumptions would at this time contribute greatly toward progress in the art of noise reduction. It is the purpose of this paper to present such a theory and to suggest how it may be used.

Generation of Air-Borne Noise By a Motor

It can be shown that the air-borne noise arising from an electric motor has as its principal source the vibration of the stator frame and yoke structure. The natural and correct assumption is that the magnetic forces set up in the air gap of the motor cause the frame structure to be distorted periodically with time and that the external surface of the frame in turn beats the air causing air-borne noise.

From the above conception of the mechanism of noise production it follows that a complete exposition of motor noise phenomena would include not only a method for determining the character, magnitude, and frequency of the disturbing forces set up in the air gap but also a means for determining the response of the stator structure to the disturbing forces.

Unfortunately, experience with tests on many motors indicates that there is sufficient variation in the response characteristics of apparently identical stator structures (assembled in complete motor)

Chart I. List of Largest Noise Force Waves

Stator Harmonic	Rotor Harmonic	Noise Frequency	Length of Magnetic Force Pole
N_f or M_f	R_f	$f[R(1-s)-1-s]$	$\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$
N_f or M_f	R_b	$f[R(1-s)+1-s]$	$\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$
N_f or M_f	T_f	$f[T(1-s)-1+s]$	$\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$
N_f or M_f	T_b	$f[T(1-s)-3+s]$	$\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$
N_b or M_b	R_f	$f[R(1-s)+1-s]$	$\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$
N_b or M_b	R_b	$f[R(1-s)+3-s]$	$\frac{\lambda}{R-N}$ or $\frac{\lambda}{R-M}$
N_b or M_b	T_f	$f[T(1-s)+1+s]$	$\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$
N_b or M_b	T_b	$f[T(1-s)-1+s]$	$\frac{\lambda}{T-N}$ or $\frac{\lambda}{T-M}$

to leave little hope that in the near future a reasonably exact expression for stator response can be presented. Calculations of stator response do have their place in a noise investigation but the results obtained thus far have been more qualitative than quantitative.

Because of the, as yet, unsatisfying results which have come from efforts to predetermine frame response characteristics no effort is being made in this paper to discuss this point. It is felt better to confine our attention to the subject of the magnetic forces causing noise and leave for the future the subject of the accurate calculation of the stator response. By presenting now that which is known for certain, effort on the part of others may be stimulated which will result in further advances in the art.

The theory will be based upon the assumption of an air gap having uniform length, constant permeance, and windings which are distributed in the usual way in finite numbers of slots. Such assumptions can be well justified in small electrical machinery where substantially closed slots are employed and where the problem of noise reaches its most acute form. In larger motors having open slots it is felt that many of the conclusions obtained by this theory will still be valuable because accompanying the use of open slots is the use of greatly increased air gaps which to a considerable extent minimize such phenomena as may arise from effects due exclusively to permeance variations. Another reason why the conclusions arrived at from this magnetomotive-force constant-permeance theory may be useful where the permeance is not really constant lies in the fact that analysis has shown that most of the phenomena arising from tooth and slot permeance variations are identical in every way with associated phenomena arising from harmonics of magnetomotive-force caused by windings placed in the same slot structure.

Development of Theory

It is well known that, in addition to the fundamental air-gap fluxes produced by the currents in the rotor and stator windings, harmonic fluxes are also produced. With symmetrical windings harmonic fluxes, with certain exceptions, may exist having a number of poles corresponding to any odd multiple of the fundamental number of poles. "Good" winding distributions generally limit the magnitude of harmonics of low order but with a given number of uniformly spaced slots nothing can be done about the magnitudes of the tooth harmonics because the "distribution factor" for the tooth harmonics is identical with that for the fundamental flux. With any given slot combination and fundamental number of poles the magnitudes and orders of the tooth harmonics are definitely determined in relation to the fundamental flux. There always exist an infinite series of tooth harmonics having magnitudes and orders as shown below.

$$\text{Order of harmonic} = \frac{\text{harmonic poles}}{\text{fundamental poles}} = 2Kn \pm 1 \quad (1)$$

$$\text{Amplitude of harmonic wave} = A_1 \frac{1}{2Kn \pm 1} \quad (2)$$

In the above equations

P_1 = fundamental number of poles
A_1 = amplitude of fundamental flux wave
n = number of teeth per pole
K = any integer

It will be noticed that the tooth harmonics go in pairs and that if there are nine teeth per pole in a 4-pole motor the largest pair of tooth harmonics are the 17th and 19th harmonics. These harmonics will have respectively 17 and 19 times as many poles as the fundamental flux and their amplitudes will be $^1/_{17}$ and $^1/_{19}$ that of the fundamental. The next largest harmonics will be the 35th and 37th and after these the 53d and 55th, etc.

There may be times when the second or third largest tooth harmonics will be important in producing noise but for the present only the largest tooth harmonics will be considered. The method outlined can be employed for any number of harmonics.

For the sake of clarity and to give a mental picture of the relative magnitudes involved, figure 1 has been prepared showing (dotted) the stair-step wave of flux produced by a four-pole winding in a 36-slot stator. Superposed is shown (solid) the fundamental component and the first pair of tooth harmonics corresponding to the stair-step wave. Both the harmonics as well as the fundamental wave of flux should be visualized as pulsating with time and, if it be assumed that figure 1 was drawn when the waves were maximum, the effect of the pulsation is exactly duplicated by dividing each pulsating wave into two oppositely gliding components each having half the amplitude shown.

If the forward and backward components be used there are now six stator flux waves to be considered. If the subscript "1" be always associated with the stator and the subscripts "N" and "M" are each associated with a member of and represent the order of the first pair of tooth harmonics, the forward and backward components of each wave may be expressed as shown below.

$$\left.\begin{aligned}
W_{1f} &= A_{1f}\cos\left[x\frac{\pi}{\lambda}-\omega t\right]\\
W_{1b} &= A_{1b}\cos\left[x\frac{\pi}{\lambda}+\omega t\right]\\
W_{1Nf} &= A_{Nf}\cos\left[Nx\frac{\pi}{\lambda}-\omega t\right]\\
W_{1Nb} &= A_{Nb}\cos\left[Nx\frac{\pi}{\lambda}+\omega t\right]\\
W_{1Mf} &= A_{Mf}\cos\left[Mx\frac{\pi}{\lambda}-\omega t\right]\\
W_{1Mb} &= A_{Mb}\cos\left[Mx\frac{\pi}{\lambda}+\omega t\right]
\end{aligned}\right\} \quad (3)$$

The forward component of fundamental stator flux acts on the rotor winding to produce a forward wave of rotor currents which in turn produces a forward wave of rotor fundamental flux moving at slip frequency with respect to the rotor. Associated with this forward fundamental

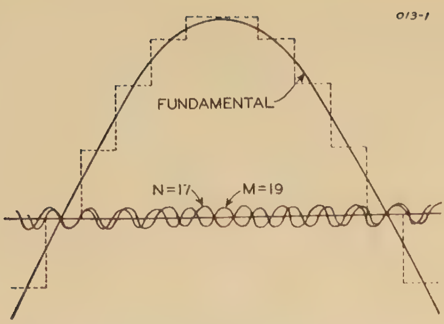

Figure 1. Fundamental and first tooth harmonics

flux is an infinite series of rotor tooth harmonic fluxes. Unlike the stator fluxes, the rotor fluxes, arising as they do from the action of a gliding wave of stator flux having constant magnitude, are not pulsating. They glide forward and backward on the rotor (forward with respect to the stator) with constant magnitude and at slip frequency with respect to the rotor.

The rotor tooth harmonics have poles and amplitudes as shown below:

$$\text{Order of rotor harmonic} = \frac{\text{harmonic poles}}{\text{fundamental poles}} = \pm\frac{2KB}{P_1}+1 \quad (4)$$

$$\text{Amplitude of rotor harmonics} = A_{2f}\left(\frac{1}{\pm\dfrac{2KB}{P_1}+1}\right) \quad (5)$$

In the above equations:

P_1 = fundamental number of poles
A_{2f} = amplitude of forward fundamental rotor wave
B = total number of rotor bars
K = any integer

When $K=0$ in equation 4, the first harmonic (the fundamental flux) is obtained and the positive sign indicates that the direction of motion of the fundamental flux wave with respect to the rotor is considered positive. A negative sign such as always occurs with the lesser-poled harmonic of each pair of tooth harmonics indicates that that harmonic is moving around the rotor in a direction opposite the motion of the fundamental flux. Throughout this discussion R indicates the negatively moving rotor tooth harmonic and the ratio of its poles to the poles of the fundamental. T will indicate the positively moving rotor harmonic and the ratio of its poles to those of the fundamental.

The backward component of fundamental stator flux is also responsible for producing a backward component of fundamental rotor flux gliding backward on the rotor at a frequency $(2-s)$ times the stator frequency. Corresponding tooth harmonics are also produced.

If only the fundamental and first pair of tooth harmonics be considered at this time there are in all six rotor fluxes. Neglecting the difference in time phase between stator and rotor currents, these six fluxes may be expressed with respect to the rotor as shown.

$$\left.\begin{aligned}
W_{2f} &= A_{2f}\cos\left[x_2\frac{\pi}{\lambda}-\omega st\right]\\
W_{2b} &= A_{2b}\cos\left[x_2\frac{\pi}{\lambda}+\omega(2-s)t\right]\\
W_{2Rf} &= A_{Rf}\cos\left[Rx_2\frac{\pi}{\lambda}+\omega st\right]\\
W_{2Tf} &= A_{Tf}\cos\left[Tx_2\frac{\pi}{\lambda}-\omega st\right]\\
W_{2Rb} &= A_{Rb}\cos\left[Rx_2\frac{\pi}{\lambda}-\omega(2-s)t\right]\\
W_{2Tb} &= A_{Tb}\cos\left[Tx_2\frac{\pi}{\lambda}+\omega(2-s)t\right]
\end{aligned}\right\} \quad (6)$$

With respect to the stator the rotor waves of (6) can be written:

$$\left.\begin{aligned}
W_{2f} &= A_{2f}\cos\left[x\frac{\pi}{\lambda}-\omega t\right]\\
W_{2b} &= A_{2b}\cos\left[x\frac{\pi}{\lambda}+\omega t\right]\\
W_{2Rf} &= A_{Rf}\cos\left[Rx\frac{\pi}{\lambda}-\omega[R(1-s)-s]t\right]\\
W_{2Tf} &= A_{Tf}\cos\left[Tx\frac{\pi}{\lambda}-\omega[T(1-s)+s]t\right]\\
W_{2Rb} &= A_{Rb}\cos\left[Rx\frac{\pi}{\lambda}-\omega[R(1-s)+2-s]t\right]\\
W_{2Tb} &= A_{Tb}\cos\left[Tx\frac{\pi}{\lambda}-\omega[T(1-s)-2+s]t\right]
\end{aligned}\right\} \quad (7)$$

The flux at every point in the air gap of the motor and at every instant of time is exactly representable as the sum of the fundamental fluxes and all the harmonic fluxes. Using those which have been considered we may write:

$$B_\delta = \left[\begin{aligned}&W_{1f}+W_{1b}+W_{1Nf}+W_{1Nb}+W_{1Mf}+\\&W_{1Mb}+W_{2f}+W_{2b}+W_{2Rf}+W_{2Rb}+\end{aligned}\right] W_{2Tf}+W_{2Tb} \quad (8)$$

The radial force density at any point in the gap due to B_δ is, according to Maxwell:

$$\frac{F}{A}=\frac{1}{72{,}130{,}000}B_\delta^2 \text{ pounds per square inch} \quad (9)$$

For purposes of noise study it is desirable to work with the components of the force density, which components are obtainable by the expansion of the square of the right member of (8). The expansion consists of the square of each term in (8) plus twice the product of each term with each other term. A complete expansion of even so few as the 12 terms chosen leads to 78 terms which are rather clumsy to handle by conventional means. In the appendix is given a simple shorthand means for performing the expansion and there has been prepared a multiplication table showing results for the case of a four-pole 36–48 combination motor.

At this time it is of interest to perform one of the multiplications in order to discuss the results obtained. In the case of the N forward stator tooth harmonic and the R forward rotor harmonic the product is:

$$\Delta F_{(Nf)(Rf)} = A_{Nf}A_{Rf}\cos\left[Nx\frac{\pi}{\lambda}-\omega t\right]\times \cos\left[Rx\frac{\pi}{\lambda}-\omega[R(1-s)-s]t\right] \quad (10)$$

$$\Delta F_{(Nf)(Rf)} = A_{Nf}A_{Rf}\times \left\{\cos\left[(R-N)x\frac{\pi}{\lambda}-\omega[R(1-s)-1-s]t\right]+ \cos\left[(R+N)x\frac{\pi}{\lambda}-\omega[R(1-s)+1-s]t\right]\right\} \quad (11)$$

It will be seen from (11) that the product of the two flux waves is representable as two force waves, the upper wave having a long wave length and the lower one having a very short wave length.

Chart II. No-Load Noise Forces for Four-Pole 36–48 Motor

Stator Harmonic	Rotor Harmonic	Frequency (Cycles)	Amplitude (Pounds Per Square Inch)	Length of Magnetic Force Pole (Inches)
17_f	23_b	1,440	0.032	0.46
19_f	23_b	1,440	0.0286	0.685
17_b	23_b	1,560	0.032	0.46
19_b	23_b	1,560	0.0286	0.685
17_f	25_b	1,320	0.0294	0.46
19_f	25_b	1,320	0.0264	0.685
17_b	25_b	1,440	0.0294	0.46
19_b	25_b	1,440	0.0264	0.685

Chart III. Magnetic Force Waves for 36–48 Combination

		Stator harmonics 1 +1		1 −1		17 +1		17 −1		19 +1		19 −1		Rotor harmonics 23 +25		23 +23		25 +23		25 +25	
Stator harmonics	1	2	0	2	0	18	16	18	16	20	18	20	18	24	22	24	22	26	24	26	24
	+1	2	0	0	2	2	0	0	2	2	0	0	2	26	24	24	22	24	22	26	24
	1	2	0	2	0	18	16	18	16	20	18	20	18	24	22	24	22	26	24	26	24
	−1	0	2	2	0	0	2	2	0	0	2	2	0	24	26	22	24	22	24	24	26
	17	18	16	18	16	34	0	34	0	36	2	36	2	40	6	40	6	42	8	42	8
	+1	2	0	0	2	2	0	0	2	2	0	0	2	26	24	24	22	24	22	26	24
	17	18	16	18	16	34	0	34	0	36	2	36	2	40	6	40	6	42	8	42	8
	−1	0	2	2	0	0	2	2	0	0	2	2	0	24	26	22	24	22	24	24	26
	19	20	18	20	18	36	2	36	2	38	0	38	0	42	4	42	4	44	6	44	6
	+1	2	0	0	2	2	0	0	2	2	0	0	2	26	24	24	22	24	22	26	24
	19	20	18	20	18	36	2	36	2	38	0	38	0	42	4	42	4	44	6	44	6
	−1	2	0	0	2	2	0	0	2	2	0	0	2	24	26	22	24	22	24	24	26
Rotor harmonics	23	24	22	24	22	40	6	40	6	42	4	42	4	46	0	46	0	48	2	48	2
	+25	26	24	24	26	26	24	24	26	26	24	24	26	50	0	48	2	48	2	50	0
	23	24	22	24	22	40	6	40	6	42	4	42	4	46	0	46	0	48	2	48	2
	+23	24	22	22	24	24	22	22	24	24	22	22	24	48	2	46	0	46	0	48	2
	25	26	24	26	24	42	8	42	8	44	6	44	6	48	2	48	2	50	0	50	0
	+23	24	22	22	24	24	22	22	24	24	22	22	24	48	2	46	0	46	0	48	2
	25	26	24	26	24	42	8	42	8	44	6	44	6	48	2	48	2	50	0	50	0
	+25	26	24	24	26	26	24	24	26	26	24	24	26	50	0	48	2	48	2	50	0
	1	2	0	2	0	18	16	18	16	20	18	20	18	24	22	24	22	26	24	26	24
	+1	2	0	0	2	2	0	0	2	2	0	0	2	26	24	24	22	24	22	26	24
	1	2	0	2	0	18	16	18	16	20	18	20	18	24	22	24	22	26	24	26	24
	−1	0	2	2	0	0	2	2	0	0	2	2	0	24	26	22	24	22	24	24	26

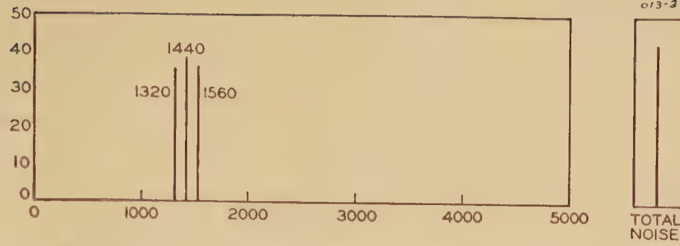

Figure 3. Noise spectrum taken on a four-pole (36–48) motor

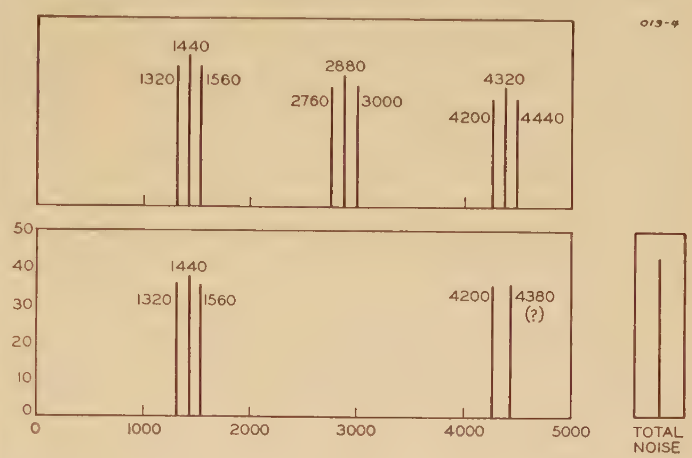

Figure 4

Top—Calculated noise-force spectrum on a four-pole (36–48) motor
Bottom—Noise spectrum taken on a four-pole (36–48) motor

In general, very short force waves will not be important because the stator will be very stiff to short-wave distortion. Long waves of force, however, will cause a relatively large response and therefore

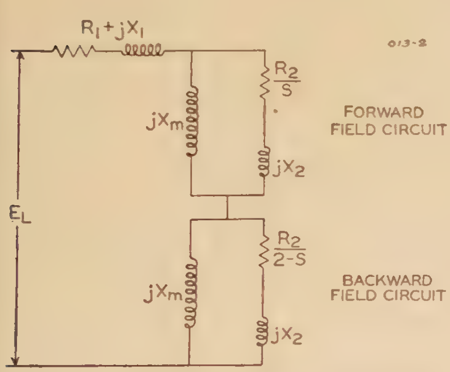

Figure 2. Equivalent circuit for a single-phase motor

will be important in producing noise. The pitch of the long force wave is:

$$\lambda_{(Nf)(Rf)}=\frac{\lambda}{R-N} \tag{12}$$

The frequency of this wave is:

$$f_{(Nf)(Rf)}=f[R(1-s)-1-s] \tag{13}$$

and this frequency is, of course, the frequency at which the air-borne noise will be emitted.

A study of the various products involved shows that those products most likely to be responsible for noise are the ones of long pitch produced by the multiplication of a stator harmonic with a rotor harmonic. There are 16 such products and they will be listed here for future reference (chart I). In appendix I a complete listing of the product terms is given but the simplifying assumption has been made that $s=0$. It may at times be desirable to have available the expression for noise frequency when $s\neq 0$.

It will be noted that the frequency does not change when the N_f stator harmonic is substituted for the M_f but the force wave length does.

Sample Force-Wave Calculation

A specific calculation will now be introduced to show how the force waves may be calculated for a particular motor.

Assumptions

Gap diameter	=3.5 inches
Stacking length	=2 inches
Stator slots	=36
Rotor slots	=48
Fundamental poles	=4
Maximum fundamental density	=30,000 lines per square inch
Maximum load current	=2 (no load current)

The order of the largest stator tooth harmonics may be calculated by means of equation 1.

$$\left.\begin{array}{l}N=17\\M=19\end{array}\right\} \tag{14}$$

The order of the largest rotor tooth harmonics may be calculated by means of (4).

$$\left.\begin{array}{l}R=23\\T=25\end{array}\right\} \tag{15}$$

At no load the forward field rotor currents are negligible (see figure 2) and the forward-field rotor tooth harmonics listed on chart I will be ineffective in producing noise. In the backward field, while the rotor and stator fundamental fluxes neutralize each other, as shown by the low voltage which exists across the backward field at no load, it will be assumed that because of poor distribution factor and spiral the harmonics exist practically undiminished.* On the basis of this assumption the stator harmonic fluxes and the backward-field rotor harmonic fluxes are subject to the same ampere turns as is the fundamental flux; consequently they will exist in their normal magnitudes (A_1/h) where h is the order of the har-

* Note: If desired the rotor secondary characteristics to each stator harmonic can be carefully calculated and an exact determination of the diminution of the stator harmonic fluxes determined. The stator winding will have almost no diminishing effect on rotor harmonics.

monic and A_1 the amplitude of the fundamental. [See (2) and (5).]

It follows that the amplitudes of the harmonics in lines per square inch are:

$$\left.\begin{array}{ll} A_{17f}=1{,}765 & A_{19b}=1{,}580 \\ A_{19f}=1{,}580 & A_{23b}=1{,}305 \\ A_{17b}=1{,}765 & A_{25b}=1{,}200 \end{array}\right\} \quad (16)$$

By the use of chart I and equation 9 it is now possible to list maximum force densities, frequencies, and wave lengths (chart II).

Chart II indicates that all the important magnetic-force waves should be small and that the principal no-load noise frequencies should be those of 1,320, 1,440, and 1,560 cycles. Figure 3 shows the results obtained by means of a noise analyzer using a four-pole 36–48 combination motor. Another spectrum, figure 4, shows that under certain conditions higher tooth harmonics may be effective.

With only three high-frequency waves of appreciable size present it might be expected that an oscillograph would trace a relatively simple pattern. Figure 5 shows two oscillographs which bear out the idea of pattern simplicity. These were taken using a velocity pickup and a high amplification to the oscillograph.

Figure 6 gives noise spectrums taken on four-pole motors of other slot combinations. These may be compared with chart VII.

The force waves under load will be larger since, as indicated under "assumptions", the maximum load current is twice the no-load current, all the stator harmonics and backward rotor harmonics will be twice as large. The forward rotor harmonics which do not exist at no load become almost as large as the others and not only are the magnitudes of the noise forces increased but the character of it is changed. (See the discussion of no-load versus load noise in appendix I.)

Chart IV

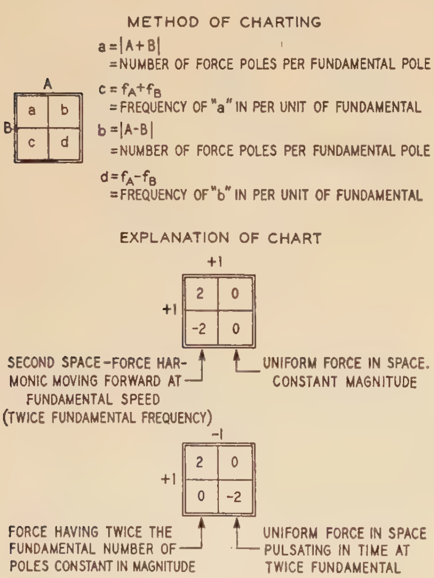

Chart V. Graphical Explanation of Chart
Two-Pole Motor Assumed

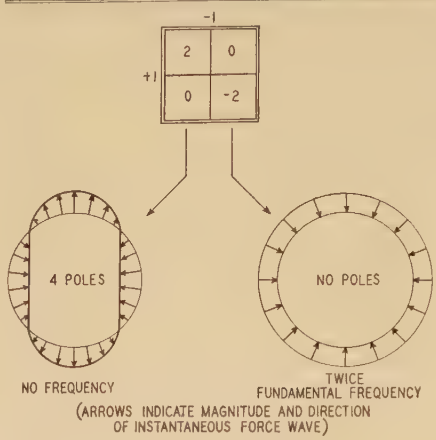

Chart VI. High-Frequency Noise Terms, 36–48 Slot Combination

ROTOR TOOTH HARMONICS	STATOR TOOTH HARMONICS 17 +1	17 −1	19 +1	19 −1	
23	6	6	4	4	a
+25	24	26	24	26	
23	6	6	4	4	b
+23	22	24	22	24	
25	8	8	6	6	c
+23	22	24	22	24	
25	8	8	6	6	d
+25	24	26	24	26	

Chart VII. Analysis of Major High-Frequency Force Waves With a 32- and a 36-Slot Stator

Stator	Rotor	Magnetic-Force Poles			Noise Frequency		
32	33	2	6	10	870	990	1,110
	34	4	12		900	1,020	1,140
	35	2	6	14	930	1,050	1,170
	36	0	8	16	960	1,080	1,200
	37	2	10	18	990	1,110	1,230
	38	4	12	20	1,020	1,140	1,260
	39	6	14	22	1,050	1,170	1,290
	40	8	16	24	1,080	1,200	1,320
36	28	8	16	24	720	840	960
	29	6	14	22	750	870	990
	30	4	12	20	780	900	1,020
	31	2	10	18	810	930	1,050
	32	0	8	16	840	960	1,080
	40	0	8	16	1,080	1,200	1,320
	41	2	10	18	1,110	1,230	1,350
	42	4	12	20	1,140	1,260	1,380
	43	6	14	22	1,170	1,290	1,410
	44	8	16	24	1,200	1,320	1,440
	48	16	24	32	1,320	1,440	1,560

Appendix I

In the calculation of magnetic force waves in the course of actual design work it is desirable to have a systematic method of work. This section of this paper describes such a method.

If time-phase relations are not important the equation for a magnetic flux wave as given in equations 3 and 7 expresses for us the following:

Amplitude
Order (pitch, distribution)
Frequency
Direction

If we deal with tooth harmonics the relation expressed in (2) and (5) is valuable in connecting amplitude with pitch so that if the pitch is known the amplitude is known. In such event only the pitch need be defined. If frequency be given a sign the symbol for frequency may be used to express both frequency and direction.

If we make these simplifications in our present case we may express any traveling wave by two numbers.* It is convenient to make these numbers "per unit" numbers as shown below. (By "per unit" is meant the expression of order and frequency as a ratio to the fundamental of each.)

$$W_a=\left|\begin{array}{c}18\\ \hline -2\end{array}\right| = \cos\left[18\times\frac{\pi}{\lambda}+2\omega t\right] \qquad (17)$$

If the upper number in the box be the order of the flux harmonic (the number of poles of the wave per fundamental pole) and the lower number the ratio of the harmonic frequency to the fundamental frequency, the wave W_a is seen to have 18 times the fundamental number of poles and to be moving backward (because of the minus sign) at twice fundamental frequency.

The conventional expression for the wave is also given in (17) and it can be seen that the numerical coefficients of the conventional expression are used in the new nomen-

*Note: It is obvious that, if desired, a four-number system could be similarly set up representing phase relation, order, magnitude, and frequency-direction. For our present purpose the simplification is desirable.

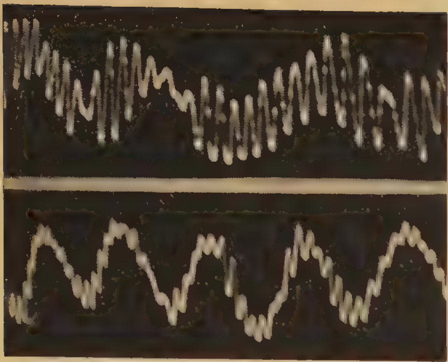

Figure 5. Cathode-ray oscillograms of stator-yoke vibration, 36–48 combination

clature except that the sign of the frequency term is reversed.

If it is desired to multiply two waves using the convention it is merely necessary to add the upper figure positive) to obtain d. The two waves are written together as at e.

If the two waves W_a and W_b are flux waves their product according to previous discussion is a pair of moving waves of force tending to bend the stator yoke into as many nodes as there are waves of force.

The present resultant force waves are seen to have 32 poles and 4 poles and to be moving respectively at twice fundamental frequency forward and at six times fundamental frequency backward. It will be noted that the numerical coefficient $^1/_2$ is dropped for simplicity in view of its existence in all similar product terms. A further simplification will be made for our present purpose in that after multiplication the sign will be dropped from the frequency terms since direction of rotation has no effect upon airborne noise in which we are primarily interested.

It was shown previously that a complete expression for the force waves of a motor would multiply each term of both the stator trated upon section "B" of the chart when high-pitch noise is of interest.

If waves of extremely short pitch be discarded as being relatively ineffective we find ourselves with the same waves given in chart VI.

It is of interest to note that the four terms laterally adjacent to "b" and "d" result from forward-field rotor current and are, therefore, absent at no load and large under load. Terms adjacent to "a" and "c," however, are the result of backward-field rotor current and are large at no load as well as under load. The results of the analysis are statistically tabulated below in relation to the number of poles of force and the frequencies produced.

	16 Poles	24 Poles	32 Poles
No-load noise forces (cycles)			
	1,440	1,320	1,320
	1,560	1,440	1,440
		1,440	
		1,560	
Additional-load noise forces (cycles)			
	1,320	1,320	1,440
	1,440	1,440	1,560
		1,440	
		1,560	

If motor noise is measured at no load it would be expected that the 1,440-cycle and 1,560-cycle noises would predominate since the stator is much stiffer to 24-node and 32-node bending than to 16-node bending. Under load the 1,320-cycle noise should become pronounced, though, due to slip, it will be somewhat displaced in frequency.

Chart VIII. Rotor Subharmonics

STATOR SLOTS	ROTOR SLOTS	SUBHARMONIC POLES / SUBHARMONIC FREQ.			
32	33	6	6	2	2
		+15.5	+17.5	−15.5	−17.5
	34	8	8	0	0
		+16	+18	+16	+18
	35	10	10	2	2
		+16.5	+18.5	+16.5	+18.5
	36	12	12	4	4
		+17	+19	+17	+19
	37	14	14	6	6
		+17.5	+19.5	+17.5	+19.5
	38	16	16	8	8
		+18	+20	+18	+20
	39	18	18	10	10
		+18.5	+20.5	+18.5	+20.5
	40	20	20	12	12
		+19	+21	+19	+21
36	40	12	12	4	4
		+19	+21	+19	+21
	44	20	20	12	12
		+21	+23	+21	+23
	48	28	28	20	20
		+23	+25	+23	+25

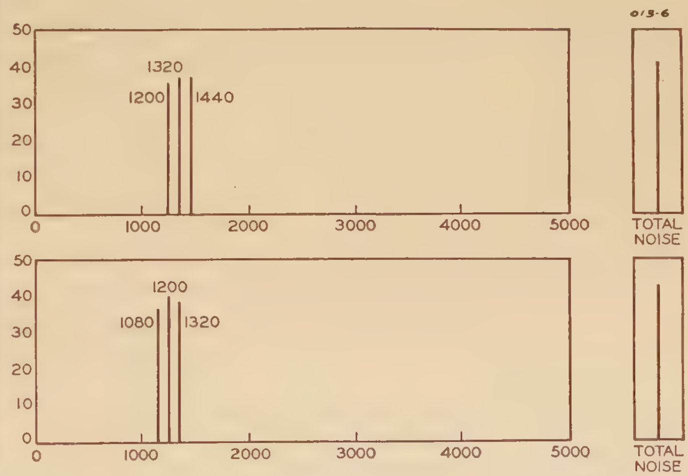

Figure 6

Top—Noise spectrum taken on a four-pole (36–44) motor

Bottom—Noise spectrum taken on a four-pole (32–40) motor

and substract numbers of the same significance. For example:

$$W_b = \left|\frac{14}{4}\right| = \cos\left[14\times\frac{\pi}{\lambda}-4\omega t\right] \tag{18}$$

$$W_a\times W_b = \left[\frac{1}{2}\cos\left[32\times\frac{\pi}{\lambda}-2\omega t\right]+\frac{1}{2}\cos\left[4\times\frac{\pi}{\lambda}+6\omega t\right]\right] \tag{19}$$

$$\underset{b}{\left|\frac{14}{4}\right|}\times\underset{a}{\left|\frac{18}{-2}\right|}=\underset{c}{\left|\frac{32}{2}\right|}+\underset{d}{\left|\frac{4}{-6}\right|}=\underset{e}{\left|\begin{matrix}32 & 4\\ 2 & -6\end{matrix}\right|} \tag{20}$$

In equation 20 a horizontal addition is made to obtain c from a and b. A horizontal subtraction is made (in the direction to make and rotor Fourier series flux expression by itself and by each other term to form a second-order series of force waves. A multiplication form has been prepared and the operations performed for a 36–48-slot four-pole combination assuming no-load operation (chart III).

Inspection of the chart will show that when stator waves act together only "0" and "2" frequencies (0 and 120 cycles) exist. It is also apparent that when rotor waves act together high-frequency terms are produced (about 3,000 cycles) but the pitches of the waves are so short that it is extremely doubtful whether the resultant stator distortion could be detected.

All of the waves found in "E" and "F" will be found in "A" and "B" respectively and "D" will be found to be a replica of "B". Attention may therefore be concen-

All no-load noises should be reduced practically to zero by polyphase operation or the use of a proper capacitor. The introduction of a balancing capacitor (effective only under load) should be accompanied not only by a reduction in noise level but by the elimination of the highest of the three tooth frequencies, causing a change of about 120 cycles in the mean pitch of the high-frequency noise. Two-phase operation should show this clearly.

Chart VII has been prepared giving principal magnetic-force waves for all the possible slot combinations for a satisfactory re-

frigeration-machine motor assuming both 32- and 36-slot stators.

It is of special interest to notice that whenever force waves of zero poles occur there exist "geared" waves of the same number of poles on the rotor and stator. The existence of such waves is accompanied by standstill locking and high-speed rotating subharmonic waves of fundamental distribution and high-frequency tooth-harmonic interference. (Discussed briefly later.)

A two-pole magnetic force tries to displace the entire rotor thus producing shaft vibration, a four-pole force tries to distort the stator yoke into the form of an ellipse, etc. It is to be assumed that, other things being equal, a magnetic force of many poles is to be preferred to one of few poles; because of the greater effective yoke stiffness when the wave length is short. Any force wave having less than eight poles is likely to be bad for noise.

Conclusions

It must be concluded that when a 32-slot stator is used the rotor is limited to 36 slots or 40 slots or more. If 36 slots are used it is questionable whether the locking and high-frequency interference (torque) noises can be kept from becoming a nuisance; spiral might control them. Above 40 slots there seems little reason to confine the slot combination to even slots if advantage is to be obtained by going to an odd number.

With a 36-slot stator the rotor possibilities are 28, 32, 40, 44, and higher. The remarks concerning the 36-slot rotor with a 32-slot stator apply to the 32- and 40-slot rotors with a 36-slot stator. Any rotor above 44 slots should be satisfactory except when the higher frequency of the produced noise is objectionable.

Appendix II. Subharmonic Waves

When the number of squirrel-cage bars is small with respect to the pitch of the exciting wave of flux it is possible for a squirrel cage to produce a flux wave having fewer poles than the exciting flux wave. In certain cases the always large stator-tooth harmonics may react upon the rotor to produce a wave of flux of fundamental distribution but rotating at such speeds as 70,000 to 80,000 rpm in a four-pole motor operating at normal 1,725 rpm speed. Such subharmonic waves become very important in the noise of a motor and must be taken into account. The procedure after determining the flux waves present is exactly as already described except that the subharmonic waves are included in the calculation along with the fundamental and tooth-harmonic waves.

Determination of Subharmonic Waves

Subharmonic waves may be determined as Chapman outlined in his book on induction motors by use of the equations:

$$S=\frac{2BK}{P_1}+h = \text{order and direction of subharmonic (direction referred to direction of } h \text{ with respect to rotor)} \quad (21)$$

$$f_s=\pm 1-\frac{2BK}{P_1} = \text{stator referred frequency in per-unit of fundamental frequency (single-phase stator)} \quad (22)$$

In the above equations:

B = total number of rotor bars
K = any positive or negative integer ($K=-1$ usually most important)
P_1 = number of fundamental poles
h = order of a stator harmonic (use plus sign always)

The magnitude of a subharmonic depends upon the rotor impedance as well as the linkage of the rotor and the stator in so far as the generating stator harmonic is concerned. If the stator harmonic is of short pitch, as are most tooth harmonics, a slight amount of spiral greatly reduces the mutual and reduces the subharmonic. Even without spiral the amplitude will usually be found to be less than $A_1(1/h)^2$. Since the calculation of subharmonic magnitudes is somewhat involved it is felt that an outline of the method is not warranted here. The intent of these remarks is merely to call attention to the effect of subharmonics.

If the stator winding is "good" and the number of rotor slots is greater than the number of stator slots by $2P$, subharmonics may usually be neglected. If the number of rotor slots is less than this subharmonics should be studied.

Chart VIII lists subharmonics for 32- and 36-slot four-pole stators when various rotors are used.

A plus sign in (21) indicates a subharmonic wave moving in the same direction as the stator harmonic, h, with respect to the rotor. Since at normal forward operating speeds the rotor is always moving forward with respect to any stator harmonic, the movement of the stator harmonic with respect to the rotor is backward. Under these conditions, if the sign of (21) is negative, it means that the subharmonic is moving in the opposite or forward direction with respect to the rotor and, of course, forward also with respect to the stator. Since a plus sign for a frequency number in chart VIII indicates a wave moving forward with respect to the stator, chart VIII would therefore have a positive frequency number when (21) is negative.

Nomenclature

A_1 = amplitude of fundamental stator flux wave
A_{2f} = amplitude of fundamental rotor forward wave
A_{NF} = amplitude of the N forward tooth harmonic
B = total number of rotor bars
B_δ = total density in the air gap at the point x
f = frequency of primary excitation
K = any integer
n = number of stator slots per pole
N = largest stator-tooth harmonic
M = second largest stator-tooth harmonic
P_1 = fundamental number of poles
R = largest (least poled) rotor-tooth harmonic
s = per unit slip
T = second largest rotor-tooth harmonic
x = distance in inches measured peripherally around the air-gap surface
ΔF = force density (pounds per square inch)
λ = fundamental pole pitch (inches)

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Current Transformers and Relays for High-Speed Differential Protection, With Particular Reference to Offset Transient Currents

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Synopsis: Up to the present time, the only data generally available to protection engineers for determining the performance of current transformers have been the ratio and phase-angle curves of the current transformers in question. More detailed analysis of important high-speed differential protection problems has shown that these data are hopelessly inadequate for the purpose of determining the performance of current transformers during the starting period when the current wave may be fully offset. If the time constant for decay of the d-c component exceeds 0.05 second, large errors of transformation may be expected if standard current transformers are used. While it is possible to make special designs that will not saturate because of the d-c component in the current,[1] such designs are usually considerably oversize and expensive. Furthermore, space requirements and economy sometimes dictate that current transformers already installed be used if at all possible, even though it is known that their performance will be far from perfect. The problem then becomes one of determining the actual performance of existing current transformers, so that a suitable relay scheme may be chosen. It is the purpose of this paper to discuss the solution of this problem, and to present approximate methods of calculation not hitherto available. Attention is also given to the proper interpretation of the calculations with respect to relay operations, together with supporting test results.

THE PROBLEM of differential protection of generating-station busses is one which almost invariably requires calculation of current-transformer performance for asymmetrical currents, because of the long time constant of the generators. Figure 1 shows schematically a six-circuit bus protected by a simple overcurrent relay. The principle of differential protection indicates that, for an external fault at X, the current, i_1 through the relay should be zero. This is based upon the assumption that all the current transformers involved will perform perfectly. Inequalities are apparent at once, however, since it is seen that the transformer in circuit F_6 carries the total fault current, whereas the others each carry only a fraction of the total. The d-c component in the primary current, particularly troublesome when large generators are near the fault, aggravates the inequalities much more severely than is immediately obvious. For example, when conditions are severe, instantaneous peak values of i_1 may be of the order of 100 amperes when the symmetrical component of the total fault current is 100 amperes rms in terms of the secondary circuit.

The false differential current, i_1, which may exist when an external fault occurs at point X, is equal to the difference between the sum of the magnetizing currents of all the current transformers carrying current into the bus, and the magnetizing current of the current transformer carrying the total fault current away from the bus. (This can be derived from figure 1 by expressing each of the secondary currents in terms of their respective primary currents less the magnetizing currents of their respective current transformers, and solving for i_1, remembering that the sum of the currents entering the bus is zero for an external fault.) This forms the explanation for the inadequacy of ratio curves for this type of problem. It diverts the interest of the protection engineer at once from the question, "What will the secondary current be?" to the question, "What will the magnetizing current be?"

The authors have found that many protection engineers tend to underestimate the relative saturating quality of the d-c component of the asymmetrical current. Some have felt that, given a definite maximum instantaneous peak value for an asymmetrical current, it was only necessary to provide a current transformer whose performance would be satisfactory on symmetrical currents having the same peak values. This is definitely not true. For these reasons, the authors believe that the discussion immediately following is in order prior to the detailed mathematical treatment. This discussion is intended to convey a conception of the mechanics of d-c saturation in a form kept as graphical as possible.

The Mechanics of Saturation

A convenient way to analyze the performance of the current transformer of figure 2*A* is by means of the equivalent diagram as shown in figure 2*B*. With a given value of primary current, i, the values of primary-winding resistance and leakage reactance are of no consequence, hence these values are not indicated in the final diagram for analysis (figure 3). Also, for convenience, the secondary-winding resistance and leakage reactance are lumped with the burden and shown as R_2 and L_2. The mutual inductance between primary and secondary windings is shown

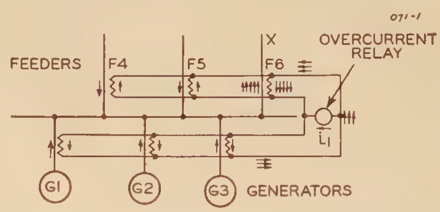

Figure 1. Simple overcurrent differential protection of a six-circuit bus

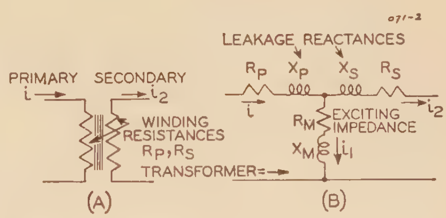

Figure 2. Diagram of current transformer and its equivalent circuit

by L_1, through which flows the magnetizing current, as indicated by i_1. It is possible to provide for the core loss current by including a suitable resistance in this branch, but this refinement is not necessary to provide sufficient accuracy for the problem at hand. This diagram is usable on the basis that the currents are expressed in terms of per cent of full-load current. Further, the diagram is usable

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1. For all numbered references, see list at end of paper.

in that, electrically, it satisfies the requirement that the primary current minus the magnetizing current must equal the secondary current. The physical significance of the current, i_1, flowing through the

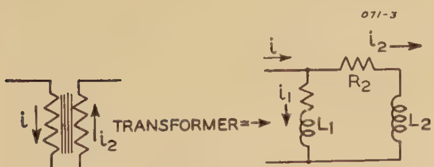


Figure 3. Simplified diagram of current transformer

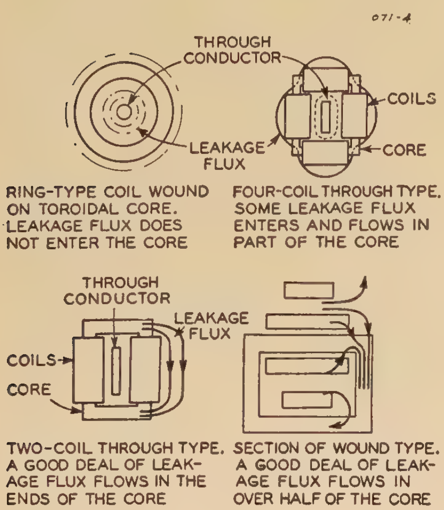


Figure 4. Leakage flux in different types of current transformers

mutual inductance, L_1, of figure 3, is that it represents in the equivalent diagram the vector difference between the primary and secondary currents in the actual transformer.

Inspection of figure 3 will show that the mutual impedance, L_1, must be kept high with respect to the burden impedance, if good current-transformer performance is to be expected. If the symmetrical current only is considered, standard current transformers are usually adequate. Actual asymmetry of the fault current requires consideration of a new and very important factor. The d-c component of the primary current must also divide between the parallel branches of figure 3. Since, to all practical purposes, there is very little impedance to direct current in the magnetizing branch, L_1, of the parallel circuit, the flow of direct current in this branch is retarded only by the inductive voltage generated by the time rate of change of the direct current, as it builds up in this circuit. The voltage which must be generated is determined by the voltage drop across the burden, R_2 and L_2, caused by the d-c component flowing through it. If the d-c time constant is long, this direct voltage must be maintained for a relatively long time, and it can only be done by a continuously increasing current through L_1 at a relatively high time rate of change. This must be done in one direction only, without the advantage of positive and negative half-cycles characteristic of alternating current. This means that the knee of the saturation curve for the inductance, L_1, may be reached within a few cycles, or within a fraction of a cycle in severe cases. When the iron core saturates, the effective value of the inductance, L_1, decreases to a fraction of the normal value. When this occurs, the ability of the mutual inductance to retard the flow of direct current through it collapses, so that practically all of the d-c component goes through L_1. This condition will continue until the d-c component has subsided, after which the transformer can again perform with its normal a-c characteristics. It is of interest and importance to note that during the time that the magnetizing branch, L_1, remains severely saturated by direct current, it also offers much less impedance to the flow of alternating current; consequently, it is to be expected that the percentage of the a-c component which is transmitted to the secondary will be materially less. These conclusions are borne out by oscillographic records which show that, when a current transformer is failing to reproduce faithfully the d-c component in the secondary, it is also breaking down in a-c ratio, even though its performance may be quite accurate on the same value of symmetrical current.

Derivation of Formulas

Mathematical analysis of the current-transformer performance is based on the same equivalent circuit, shown in figure 3, and in fact, has already been worked out by Marshall and Langguth.[1] Their paper gives rules for keeping the flux density below the saturation value and for calculating performance, provided the transformer does not saturate, but, of course, cannot be used to indicate performance in cases where there simply is not room for the resulting design, or where existing transformers must somehow be used. The following analysis will be devoted to methods for calculating the performance, after saturation is reached. Important savings in space, as well as in weight and expense, may result if the analysis shows that current transformers which are far from perfect may still be adequate.

General Considerations

Returning to figure 2*B*, it must be recognized that although the sum of the leakage reactances, X_p and X_s, may be nearly constant and represent definite flux linkages, the effective division between X_p and X_s is different for every load condition, and they are individually practically impossible to determine.

Most problems deal with the "through" or "bar" type of current transformer, which can be so designed that the leakage flux which enters the core is negligible, and the following theory has, therefore, been worked out on the basis that the secondary leakage reactance is zero. The theory cannot be indiscriminately applied to wound-type transformers nor to through-type transformers with coils only on two legs of the core (see figure 4) without preliminary investigation of the relative amount of leakage flux.

The theory described assumes that the reactance of the burden is also zero. The justification for this is difficult to establish rigorously, but it can be readily estimated that once the d-c component of current is established (as it is during the first half-cycle) the inductance in the burden will present no obstacle to maintaining it, while the resistance in the burden acts against the direct current with a more or less continuous counter (IR) voltage. The

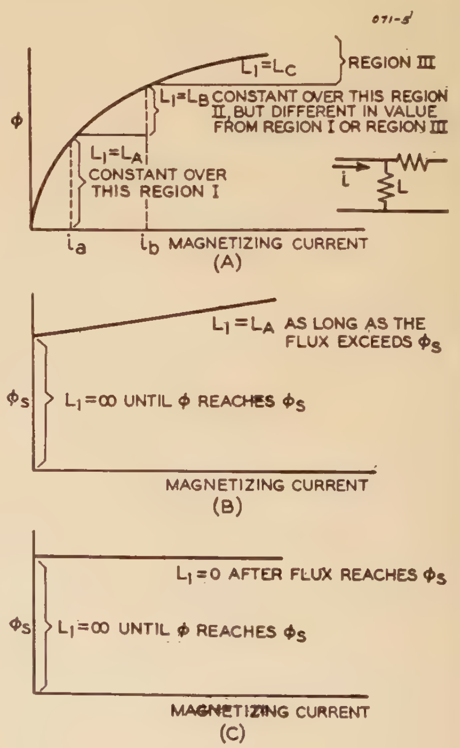


Figure 5. Approximations of the saturation curve

The true saturation curve may be approached as closely as may be desired

theory has been worked out and calculations made with inductance in the burden, and it has been found that it makes very little practical difference in the result if the inductance is neglected, at least for burden power factors of 80 per cent or more. Tests confirm this.

The value of the assumption that $L_2=0$ is that the numerical work of calculation is approximately halved. After an example has been worked out, the importance of this becomes obvious. In the short-cut method to be described later, the secondary inductance may be included, but it can be shown that it can be neglected with negligible error.

The final assumption is that the equivalent resistance of the magnetizing branch of the network is zero. Correctness of this assumption is more difficult to prove, but actual results indicate that it is always practically true.

Fundamental Equations

The equivalent network to be analyzed is thus very simple, figure 3, and may be analyzed exactly as Marshall and Langguth have previously done, except that $L_2=0$.

The equation for the difference current will be the same as given by Marshall and Langguth (equation 15, corrected) in their paper, except to neglect L_2.

$$i_1=\frac{1}{R_2T_1}\epsilon^{-t/T_1}\int R_2 i\epsilon^{t/T_1}\,dt+C\epsilon^{-t/T_1} \qquad (1)$$

where $T_1=L_1/R_2$.

If the circuit is closed at the moment to get a fully offset primary current:

$$i=I(\cos\omega t-\epsilon^{-t/T}) \qquad (2)$$

Substituting for i and performing the indicated integration gives:

$$i_1=I\left[\frac{\cos(\omega t-\Delta)}{\sqrt{1+(\omega T_1)^2}}-\frac{T}{T-T_1}\epsilon^{-t/T}\right]+C_1\epsilon^{-t/T_1} \qquad (3)$$

$$\Delta=\tan^{-1}\omega T_1$$

$$T_1=\frac{L_1}{R_2}$$

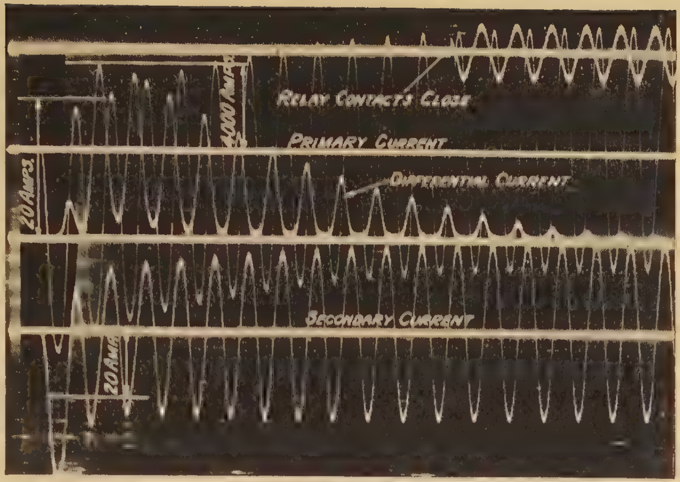
This equation is perfectly general, and is the one on which the calculation of exciting current will be based. Its limitation in actual use is that L_1 (and T_1) are assumed to be constant; in the actual problem the solution must be carried out into the region of saturation, and L_1 (and T_1) will vary.

Step-by-Step Solution

Three-Zone Saturation Curve

Any saturation curve can be represented as closely as may be desired by a number of straight lines. This makes it possible to consider the inductance constant in a given region, as in figure 5A. With such an approximate curve, the magnetizing current may be calculated by means of equation 3. The procedure is to begin at time, $t=0$, setting $L_1=L_A$, $i_1=0$, evaluate C_1, and calculate i_1 at various values of t. It must be remembered that each time that i_1 enters a new region, figure 5A, the value of L_1 must be changed correspondingly, and a new value of C_1 obtained. This procedure gives good results, but is very laborious, and quite impractical for most problems. Further simplification is desirable.

Figure 6A. Oscillogram showing that nonsaturating current transformer (primary current) balanced against current transformer that saturates (secondary current) gives a false differential current



Primary current, 4,000 amperes rms, $T=0.075$, ratio 1,000/5, test current transformer core area 1.69 square inches, secondary resistance 1.05 ohms

Two-Zone Saturation Curve

It will usually be found that the exciting current will be negligible in its effect on the differential relay until the upper region of the saturation curve is reached. This justifies the assumption of a more simple shape of the saturation curve, as in figure 5B. The advantage of this shape is that L_1 is infinite until the "saturation" flux is reached, and the boundary conditions at the same time, t_1, at which ϕ_s is reached are: $t=t_1$, $i_1=0$. Returning to equation 5 in the paper by Marshall and Langguth, the flux will be (letting $L_2=0$ and writing I_s for N_pI_p/N_s)

$$\phi=\frac{10^8 I_s}{N_s}\left[\frac{R_2\sin\omega t}{\omega}+R_2T\epsilon^{-t/T}\right]+C \qquad (4)$$

The procedure of calculation will be:

1. Calculate the flux variation beginning at time, $t=0$, $\phi=0$. Evaluate C accordingly, and calculate ϕ at several intervals of time, t, as necessary to determine the time, t_1, at which the flux will reach the "saturation" value, ϕ_s.

2. The new boundary conditions to be used now in equation 3 will be $t=t_1$, $i_1=0$. Evaluate C_1 and calculate i_1 at suitable intervals of time. Inspection of the equation shows that i_1 may be maintained at a positive value for a considerable length of time if the values of t, C_1, and T are suitable.

3. However, i_1 will eventually pass through zero. When it does at time, $t=t_2$, we must return to the equation 4 for ϕ and substitute the boundary conditions, $t=t_2$, $\phi=\phi_s$. The variation of ϕ must then be calculated. Usually, it will return to the "saturation" value of ϕ_s within a fraction of a cycle, say at time, t_3.

4. At time, t_3, $i_1=0$, determine a new value of C_1 and continue calculation of i_1.

This procedure might appear to be fully as difficult as that of the first method. Actually, it is much easier, and usually gives results which are not appreciably different.

If circuit constants are such that the exciting current (paragraph 2 above), is maintained at a positive value for a number of cycles, equation 3 shows that this exciting current is composed of a sinusoidal component with two superimposed d-c components. Unless the top of the saturation curve has an appreciable curvature, there will be few harmonic components in the exciting current. The variation of flux may occur over a relatively short zone along the top of the saturation curve, which may be nearly straight. Of course, the actual flux variation is always along a superimposed hysteresis loop, and the equivalent degree of curvature with the resulting harmonic components cannot be practically determined on any exact basis. However, tests show that the actual differential current may often be very nearly sinusoidal.

Flat-Top Saturation Curve

A still more simple method is to assume that the saturation curve has a flat

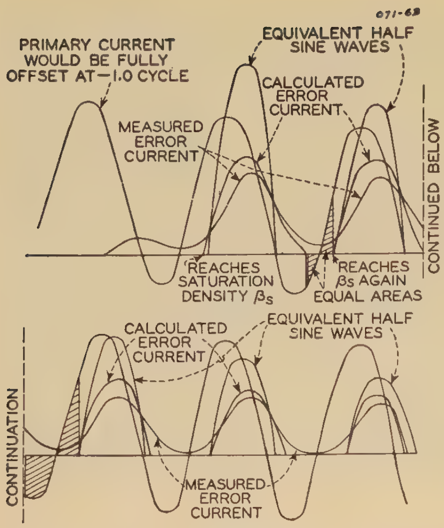


Figure 6B. Check of calculated error current against measured error current of figure 6A

The lower section of the figure is a continuation of the upper section. The "calculated error current" was calculated by the step-by-step method, equation 3 and sloped-top saturation curve, and the "equivalent half sine waves" were calculated using equation 12

Constants for calculated error current: $I=28.3$, $T=0.075$ ωL_1 corresponding to slope of top of saturation curve $=1.37$, $R_2=1.05$, $A=1.69$ square inches

top, so that L_1 will be zero after saturation (figure 5C) and the current equation will become:

$$i_1=I(\cos\omega t-\epsilon^{-t/T})$$

This is the same as the expression for the primary current, and shows, as would be expected, that if the saturation is complete at density, ϕ_s, there is no further reproduction of current in the secondary circuit until the time during the cycle when the primary current again passes through zero. At this time, the flux will tend to decrease below ϕ_s and the primary current will, thereafter, be perfectly reproduced until the flux once more increases to ϕ_s.

Figure 6B shows the exciting current as measured, and as calculated according to the sloped-top, and the flat-top saturation curve, compared with test values, for a given example. It can be seen that the calculated values according to both methods are in fair agreement with the test values.

Approximate Formulas

All these methods involve a great deal of numerical work. They are entirely too difficult for use in making the large number of preliminary estimates of performance which must be made during the study of a system of protection for a given bus layout. A still more simple solution is based on some rather bold assumptions. The justification of these assumptions will be shown to be two-fold:

1. The assumptions will be such that the final result will be pessimistic.

2. The results will agree sufficiently well with actual tests to be generally useful.

Returning to figure 6B it will be seen that the measured exciting current exhibits the following characteristics:

1. The area under the test current wave is very nearly the same as the area under the calculated current wave.

2. The exciting current wave form is approximately that of a half-wave rectified current.

These characteristics are shown in a large number of oscillograms, some of which are shown in figures 6A, 10A, and 10B.

From these considerations we will make the following assumptions:

1. The exciting current can be calculated and dealt with on the basis that it will always be a half sine wave.

2. The magnitude of it can be calculated on the basis that the area under the half wave will equal the area under the exciting current wave calculated by the previously described method.

The meaning, and the advantage of assumption 2 will be apparent from the consideration that the area of the exciting current wave can be determined fairly simply from the fundamental equation:

$$N\frac{d\phi}{dt}10^{-8}=R_2i_2$$

$$N\phi 10^{-8}=10^{-8}\int Nd\phi=R_2\int i_2dt \qquad (5)^*$$

and the consideration that ϕ will be at the saturation value at both beginning and end of a cycle, and that if the integration is from beginning to end, $N\phi$ must, therefore, be zero. The equation then becomes simply:

$$R_2\int_{t=(n+1)T_0}^{t=nT_0} i_2dt=0 \qquad T_0=\frac{1}{f} \qquad (6)$$

However, the actual integral of an asymmetrical primary current over a cycle is obviously not zero. The meaning of this is that the whole value of the integral of primary current is exciting current, and will flow through the differential circuit. This integral is easily evaluated and can be shown to be (see appendix I):

$$\int_{t=(n+1)T_0}^{t=nT_0} idt=IT_0\epsilon^{-nT_0/T} \qquad (7)$$

for any given cycle, n. Now, if the area under the exciting wave is $IT_0\epsilon^{-nT_0/T}$ according to (7), the magnitude of its peak value can easily be determined, if the assumption is maintained that the exciting current will appear as a half sine wave. The area under a half sine wave is (see appendix I):

$$A=\frac{PT_0}{\pi} \qquad (8)$$

where

P = peak value
T_0 = time of one cycle

If the area is given by (7), the peak value can be obtained from (8) and (7).

$$P=\frac{\pi A}{T_0}=\pi I\epsilon^{-nT_0/T} \qquad (9)$$

This expression for value of any exciting current peak at the nth cycle can be very quickly evaluated.

Determination of the time at which the saturation value of flux is reached can be made from equation 4. This equation cannot be solved for t as it stands, but if we make the pessimistic assumption that the sinusoidal component is always at its maximum value—

$$\frac{R_2\sin\omega t}{\omega}=\frac{R_2}{\omega}$$

then the equation can be solved for t, giving

$$t=-\frac{T}{0.434T_0}\log\left[1-\frac{\beta_sNA}{10^8R_2TI}+\frac{1}{\omega T}\right] \qquad (10)$$

If an impedance, Z_D, is connected into the differential circuit, it obviously will reduce the differential current. If the resistance were zero, the effect of inductance would be to reduce the variation in current, but to allow about the same magnitude of d-c component. If the inductance were zero, the resistance would continuously oppose the current, reducing it at every point on the wave.

If the differential current is calculated on the basis that the inductance in the differential circuit is negligible, the calculated value will certainly be somewhat too high, and the result will be in error on the conservative side. Referring to figure 9, we can rewrite (5)—

$$e_s=\frac{Nd\phi}{dt}10^8=R_2i_2-R_Di_1 \qquad (11)$$

Considering, as before, that ϕ will have to be the same, and equal to ϕ_s at the end of each cycle, it can be shown that (ap-

* $L_2\frac{di}{dt}$ may be included in this equation, but it can be shown that the resulting integral L_2i will be negligible for any usual problem.

pendix II) the differential current will be a fraction of the value calculated from the assumption that the resistance in the differential circuit is zero, or

$$P = \pi I \epsilon^{-nT_0/T} \frac{R_2}{R_D + R_2} \text{ (peak amperes)} \quad (12)$$

The methods used may seem to lack mathematical rigor. Indeed they do, but the assumptions are all uniformly pessimistic, and cannot well cause errors which destroy the practical value of the result. Comparison with tests show that the results are sufficiently accurate to be useful.

Relay Characteristics

The operating characteristics of relays are usually given in terms of symmetrical sine-wave quantities. Also, when current-time curves are taken, the current is usually left on until after the contacts have closed and the time determined. Consideration of the characteristics of the expected differential current reveals at once that it is not always sinusoidal nor symmetrical, and that it does not necessarily last for a length of time sufficient to cause the relay contacts to close, depending, of course, upon the time setting of the relay being used. For the differential problem, additional data are needed. These cover relay performance on altered wave forms involving various amounts of d-c and current-time curves wherein the current is applied only for a limited time. The latter curves will be termed "impulse curves" for convenience.

It is impossible to duplicate in the relay testing laboratory all of the possible currents which may occur in the differential circuit when all the variations between applications and between different possibilities for one application are considered. The best that can be done is to take data of a general nature which may be approximately interpreted for the particular application. Consideration of a large number of test oscillograms lead to the following conclusions:

1. The differential current for two or more cycles may be fairly represented in many cases by a fully and continuously offset sine wave. These few cycles, then, represent those test conditions wherein the harmonics present in the differential current are of minor consequence. The condition is easily set up by passing both steady-state direct current and sine-wave alternating current through the relay coil at the same time.

2. Subsequent cycles of the differential current may be fairly represented by half-wave rectified current. This approximation is sufficiently accurate until the differential current has subsided to a point where it is negligible in comparison with the original peak values.

A comparison of a standard current-time curve with impulse curves is given in figure 8 for a standard-type *COH* overcurrent relay. Each of the four curves was taken with the same tap and time-lever setting. The abscissas are plotted in terms of peak amperes rather than rms amperes in order that the approximate formula (9) or (12) for differential current may be most useful. Curve *a* is the usual current-time curve where the current is not interrupted until after the contacts close. For curve *b*, however, sine-wave 60-cycle current was applied only for the length of time shown by the time scale, and then interrupted. After the current was interrupted, the contacts closed due to kinetic energy stored in the disk. The total elapsed time from the application of current until the contacts closed is not shown by the curve at all. Thus, this curve is an "impulse curve", indicating a product of current and time which will store just sufficient kinetic energy in the relay disk to cause the contacts to close. Curve *c* is a similar impulse curve, except that half-wave rectified current was used. Curve *d* is a similar curve for a fully offset sine wave, where the direct current through the relay was made equal to 1.414 times the a-c sine-wave amperes. Curves *c* and *d* compared with curve *b* show the effect of a d-c component. Also, for the same peak-current values, curves *c* and *d* have less rms and 60-cycle component values. Curves *c* and *d* differ from each other because of the proportion of the direct current being different and because there are harmonics in the half-wave current.

Confirming Tests

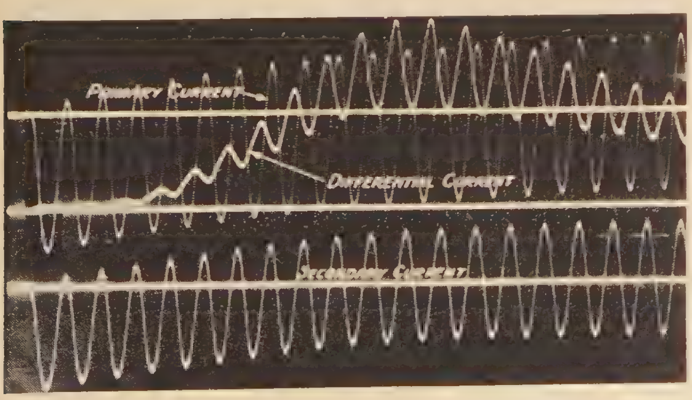
The approximate methods of calculating the current-transformer performance, as given, and the proper interpretation of the results in terms of impulse characteristics of the relays would have no value, of course, if it were not possible to verify the predictions made by means of suitable tests. Confirming tests have been made with results as given below.

Test Setup

Figure 9 shows the essential details of the test setup which was used. The circuit for demagnetizing the current transformers between tests is not shown. The nonsaturating current transformer shown was liberally designed so that it would not saturate under any of the test conditions. For this reason, the oscillographic record of i was taken as the true picture, in terms of the secondary, of the primary current. At the same time, the current, i, may be taken to represent the total output of any number of current transformers carrying current into a bus for an external fault, as in figure 1, on the basis that these current transformers do not saturate. This is a legitimate simplification of test setup, since nonsaturation of the input current transformers gives the maximum difference current, i_1, for a given saturation of the outgoing current transformer. Thus, the most pessimistic condition is arrived at at once with a decided simplification of test.

The resistor, R_2, was used to obtain various degrees of saturation of the test current transformer. The resistor, R_D, was

Figure 7. Test oscillogram showing error current with high percentage of direct current



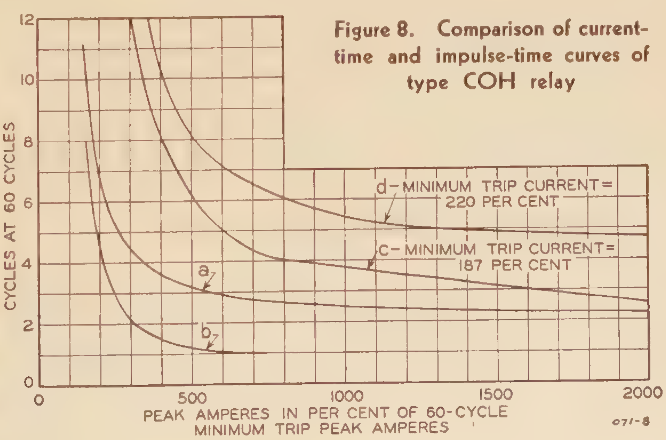


Figure 8. Comparison of current-time and impulse-time curves of type COH relay

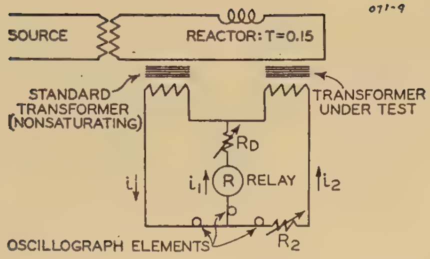


Figure 9. Diagram of test circuit

used to explore the possibility of preventing the false operation of a simple overcurrent differential relay by this means, and to check the accuracy of equation 12 showing the reduction in differential current expected.

As usual in tests of this kind, the current wave shape which can actually be obtained is not the perfect shape assumed in the theory, and the test results have to be properly interpreted to take the actual variation into account. The actual wave departs from the theoretical as follows:

1. It is never perfectly offset.

2. The output from a power transformer will contain not only a d-c component in proportion to the primary d-c component, but also a secondary d-c component determined by the constants of the secondary circuit. As a result, the secondary current, if initially offset on one side of zero, always becomes slightly offset on the opposite side before the transient finally disappears. The apparent decrement toward the end of the transient is higher than at the beginning, and higher than would be predicted from the true time constant L/R of the circuit.

3. There seems to be a higher decrement over the first cycle of current, probably due to the contact not being solidly closed initially.

The test results were, therefore, analyzed as follows:

1. The time constant was determined by plotting the logarithm of the average value of current. When the time constant departed to an appreciable extent from the true value (toward the end of the transient) the test and calculation do not agree, and this fact was simply accepted as unavoidable.

2. The logarithm of the average value plotted against time was projected back to the value it should have if the wave were fully offset, and it was always found to occur at a negative value of time. The calculations were then made on the basis that the current was fully offset, but that the transformer flux started at zero at some equivalent time corresponding to the real beginning of the current. That is, if the current was such that it would have been fully offset at -1.0 cycle (one cycle before the actual beginning) the time of saturation of the transformer can still be calculated by assuming that the flux starts from zero at $t=1$ cycle and the successive values of differential current calculated using $n+1$ instead of n in equations 9 and 12.

Table I

$I=28.3 \quad R_2=1.05 \quad R_D=0.38$

$\hat{P}$ = Peak Value of Differential Current

n_{osc}*	n_{eff}†	$P=\frac{1.05}{1.43}\pi I\epsilon^{-nT_0/T}$	P Test Figure 10A	Calculated Cycles From Figure 8c: From Calculated P	Calculated Cycles From Figure 8c: From Test P	Reciprocals**: Column 5	Reciprocals**: Column 6
0	1		2.04				
Saturation occurs here							
1	2	41.4	17.9	3.2	4.8	0.310	0.208
2	3	33.3	18.36	3.5	4.7	0.286	0.213
3	4	26.6	16.0	3.9	5.4	0.256	0.185
4	5	21.3	13.8	4.2	6.3	0.238	0.159
5	6	17.1	11.6	5.0	7.9	0.200	0.127
6	7	13.7	9.88	6.5	9.5	0.154	0.105
7	8	11.0	8.31	8.4	12.5	0.119	0.080
8	9	8.75	6.75	12.0	18.0	0.083	0.055
9	10	7.02	5.64	18.0	24.0	0.055	0.042
10	11	5.67		24.0		0.042	
						1.743	1.174

* n_{osc} denotes the number of the cycle on the oscillogram.

† n_{eff} denotes the number of the cycle on counting from time, $t=-1.0$ cycle where the current would have been fully offset.

** The reciprocals indicate a percentage of the energy required to operate the relay. Thus, if three cycles of a given peak current are required to close the contacts, then each peak delivers one-third of the total energy needed.

This sort of interpretation is awkward and not as straightforward and clear as might be desired, but is hardly to be avoided. If an a-c generator is used to supply the current, the difference between transient and subtransient reactance will reduce the initial a-c component, with the result that a wave which is initially fully offset may be more than fully offset during the second or third cycles, which will also require interpretation. It is obvious that the possible impulses of differential current can safely be calculated on the basis that the a-c component is maintained at the value corresponding to the subtransient reactance. Therefore, whether the current source is a generator or a transformer, the calculated differential current will always be somewhat higher than the actual value, providing that the current is based on the subtransient reactance of the generator.

The perfect current transformer used as a standard had about ten times the cross section of core and about one-fifth the resistance in its circuit of the transformer under test, and calculation showed that its flux density never exceeded the value corresponding to maximum permeability, so that it can safely be considered to be perfect. The other transformers in an actual differential protection circuit may not be perfect. If they are not, the actual differential current will be even less, and a perfect transformer balanced against a poor one represents a worst possible condition.

Taking all these considerations into account, a large number of tests were made and compared with calculations.

Test Results

The first set of tests was made with negligible resistance in the differential

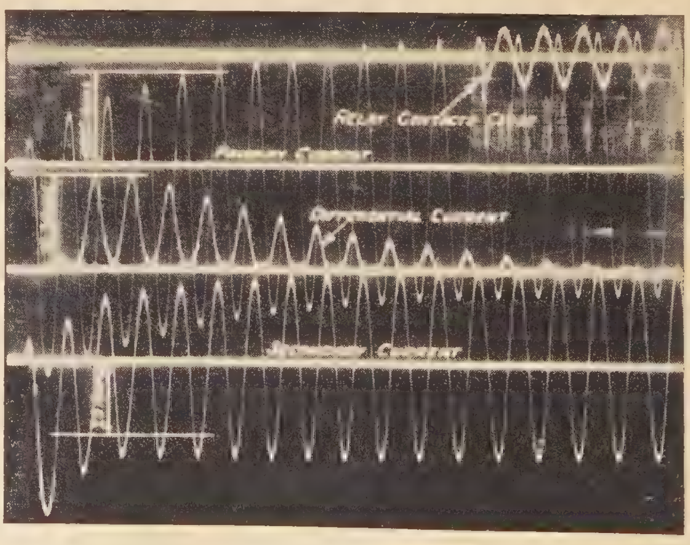


Figure 10A. Oscillogram made under the conditions of table I. Relay contacts close at the 12th cycle

circuit. The differential current was calculated according to equations 3 and 4, and a very good agreement obtained (figure 6). It was also calculated according to equation 12, and it can be seen that the equivalent half sine waves are much larger than test values to begin with, but are in fairly good agreement with test after the first few cycles.

The next step was to introduce resistance into the differential circuit. With a burden resistance of 0.82 ohm and a differential resistance of 0.38 ohm, the oscillogram of figure 10*A* was taken. The primary current lacked one cycle of being fully offset; that is, it would have been fully offset at −1.0 cycle. The time to saturation, calculated by equation 10, is 0.95 cycle. Taking this as 1.0, the equivalent time at which saturation would occur is actually about 2.0 cycles, and the successive calculated peaks (equation 12) of differential current are given in table I with the test values scaled from figure 10*A* for comparison.

The number of cycles which each peak would have taken to operate the relay (taken from figure 8) are given in columns 5 and 6 of table I, and the reciprocals of the numbers of cycles in columns 7 and 8. The sums of these columns are 1.74 and 1.17 respectively, and both indicate that the relay should operate. The relay actually operated about once in six times of application of current, and always operated when the current was offset as in figure 10*A*.

When the differential resistance is increased to 0.75 ohm, the oscillogram, figure 10*B* results and the corresponding peaks are given in table II. The sum of the reciprocal column based on calculated current indicates that the relay should operate. Actually, the relay could not be made to operate.

These tests indicate a considerable factor of safety. A large number of tests and calculations have been made, some of which show no factor of safety at all, and one test showed an actual operation when the calculated sum was only 0.8. This test indicates that if nonoperation is to be guaranteed, the sum of the reciprocal column should be held to something less than 0.8. A sum of 0.5 has been taken as a very safe value. If saturation occurs during the first two or three cycles, consideration of the possible differential current shows that each peak will have to last longer than one-half cycle and will, therefore, have a smaller peak value. Therefore, a larger factor of safety can be counted on if saturation occurs very soon than if it occurs later.

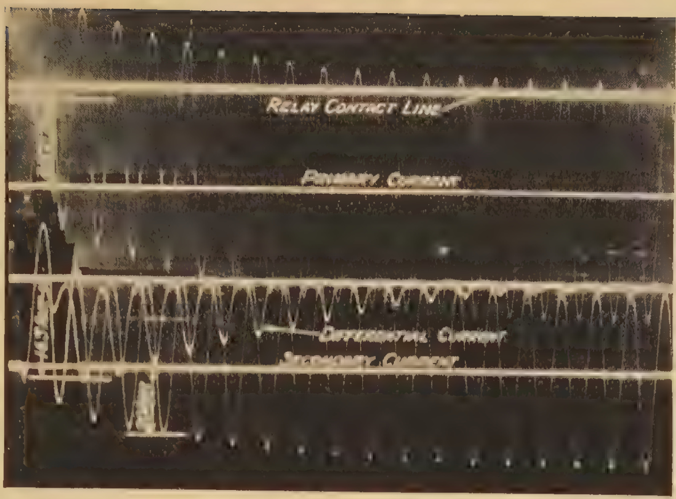


Figure 10B. Oscillogram made under the conditions of table II. Similar to table I, except that $R_D = 0.75$ ohm. The relay does not operate

The test results which can be presented here are necessarily limited, so that they cannot adequately cover the entire range of possibilities. A large number of tests have been made, however, with sufficient results to justify the methods covered in this paper and are sufficiently general to warrant the following discussion.

In figure 10, for example, it is noted that the first few cycles of differential current are composed almost entirely of a d-c component and a sine-wave component. Obviously, its form is different from half wave, but the half-wave impulse curve of the relay was used in predicting relay operation. A better prediction could have been made by using impulse curve 8*d* for the first few cycles. However, curve 8*d* shows that the combined direct current and sine wave is less effective in operating the relay, and it is thus concluded that the use of curve 8*c* errs on the conservative side. From the point of view of simplification, as well as insuring that errors will always be on the conservative side, it is better to use curve 8*c* only, neglecting curve 8*d*.

Other Relays

The tests described were made with a simple overcurrent relay. In many cases, such a relay is not adequate for bus differential protection. The type *CA*-6 relay, which is a ratio-differential relay of the variable-ratio type, may be used where the requirements are more severe. With this relay, the same method of calculation of the peak values of the differential current may be used, of course. In considering the impulse characteristics, however, the effect of through fault current restraint is very important and helpful in allowing a much greater degree of current transformer saturation without causing a false tripping operation for a through fault. The impulse curves for the type *CA*-6 relay are quite similar to curve *c* of figure 8, except that they are moved considerably to the right, even with moderate restraint values.

Conclusions

1. The methods of approximate calculations outlined provide a tool for the analysis of current-transformer performance which has not been available previously.

2. The resulting predicted current in differential relay circuits is sufficiently accurate

Table II

$I = 28.3 \quad R_2 = 1.05 \quad R_D = 0.75$

P = Peak Value of Differential Current

n_{osc}	n_{eff}	$P = \frac{1.05}{1.8}\pi I\epsilon^{-nT_0/T}$	P Test Figure 10B	Calculated Cycles From Figure 8c: From Calculated P	Calculated Cycles From Figure 8c: From Test P	Reciprocals: Column 5	Reciprocals: Column 6
0	1		4.5				
Saturation occurs here							
1	2	32.8	14.3	3.6	6.0	0.278	0.167
2	3	26.4	13.9	3.8	6.4	0.263	0.156
3	4	21.1	11.6	4.2	8.0	0.238	0.125
4	5	16.9	10.0	5.0	9.5	0.200	0.105
5	6	13.6	8.6	6.4	12.0	0.156	0.083
6	7	10.9	7.5	8.4	15.3	0.119	0.066
7	8	8.73	6.35	12.0	20.6	0.083	0.049
8	9	6.95	5.28	18.0		0.056	
						1.393	0.751

for determining relay schemes and settings because the approximations which it has been necessary to make have been uniformly made on the pessimistic side.

3. The use of impulse curves of relays is of material value in reducing the amount of safety factor to allow because of unknown factors.

4. It is felt that the agreement between calculated results and test results, while not perfect, is sufficiently close to warrant the use of the method by protection engineers. Because of the variations noted, however, it is recommended that a safety factor of about 2 should be applied in relay work.

Appendix I

Evaluation of

$$\int_{t=(n+1)T_0}^{t=nT_0} idt$$

$$i=I(\cos \omega t-\epsilon^{-t/T})$$

$$\int_{t=(n+1)T_0}^{t=nT_0} idt=$$

$$I\left[\frac{\sin \omega t}{\omega}+T\epsilon^{-t/T}\right]_{t=(n+1)T_0}^{t=nT_0} =$$

$$IT\left[\epsilon^{\frac{-nT_0}{T}}-\epsilon^{\frac{-(n+1)T_0}{T}}\right]=$$

$$IT\epsilon^{\frac{-nT_0}{T}}\left[1-\epsilon^{\frac{-T_0}{T}}\right]$$

T/T_0 must be at least 3 in any problem of importance, because if the transient has a time constant less than three cycles long, it may usually be neglected. Hence, T_0/T will be less than 0.33 and if we write the series for $\epsilon^{-T_0/T}$:

$$\epsilon^{-T_0/T}=1-\frac{T_0}{T}+\left(\frac{T_0}{T}\right)^2\cdot\frac{1}{\underline{/2}}\ldots\text{etc.}$$

and

$$\frac{1}{\underline{/2}}\cdot\left(\frac{T_0}{T}\right)^2$$

and higher terms can be neglected.

Hence:

$$\int_{t=(n+1)T_0}^{t=nT_0} idt=IT_0\epsilon^{-nT_0/T}$$

Evaluation of area under a half sine wave of peak value P:

$$\text{Area}=P\int_{t=0}^{t=\pi/\omega} \sin \omega t dt$$

$$=P\left[-\frac{\cos \omega t}{\omega}\right]_0^{\pi/\omega}$$

$$=\frac{2P}{\omega}=\frac{2P}{2\pi f}=\frac{PT_0}{\pi}$$

If the area of the integral

$$\int_{t=(n+1)T_0}^{t=nT_0} idt=IT_0\epsilon^{-nT_0/T}$$

is to be set equal to the area under the equivalent half sine wave, PT_0/π:

$$\frac{PT_0}{\pi}=IT_0\epsilon^{-nT_0/T}$$

the equivalent peak value is $P=\pi I\epsilon^{-nT_0/T}$.

Appendix II

Derivation of equation 12, considering effect of resistance in differential circuit: Continuing from equation 11, and following the same reasoning as in going from equation 5 to equation 7:

$$e_s=N\frac{d\phi}{dt}10^{-8}=R_2i_2-R_Di_1$$

or

$$N\frac{d\phi}{dt}10^{-8}=R_2i_2-R_Di_1$$

$$N\phi=N\int d\phi=0=R_2\int i_2dt-R_D\int i_1dt$$

$$\int i_2dt=\frac{R_D}{R_2}\int i_1dt$$

but

$$i_1=i-i_2$$

and

$$\int i_1dt=\int idt-\int i_2dt=\int idt-\frac{R_D}{R_2}\int i_1dt$$

Then

$$\int i_1dt=\frac{R_2}{R_2+R_D}\int idt$$

As in appendix I, if we express the area,

$$\int_{t=(n+1)T_0}^{t=nT_0} i_1dt=\frac{PT_0}{\pi}$$

the equivalent half sine wave and

$$\int_{t=(n+1)T_0}^{t=nT_0} idt=IT_0\epsilon^{\frac{-nT_0}{T}}$$

we have

$$\frac{PT_0}{\pi}=\frac{R_2}{R_2+R_D}IT_0\epsilon^{\frac{-nT_0}{T}}$$

and

$$P=\frac{R_2}{R_2+R_D}\pi I\epsilon^{\frac{-nT_0}{T}} \qquad (12)$$

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Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Transactions

Preprint of Technical Papers Comprising Pages 489–562 of the 1940 Volume

Electric Braking for Railroad and Urban Transit Equipment

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THE PURPOSE of this paper is to outline the present status of electric braking in the railroad and urban transit fields and to point out possible solutions of future braking problems particularly those arising from increasing speeds.

General

The science of train braking has progressed steadily with the development of railroad transportation. Improvements in air brakes along with improvements in motive power and rolling stock have made possible the steadily increasing speed and length of trains; in fact, the railroad industry as we know it today. With the exception of a few railway electrifications where regenerative electric braking has been applied, this entire development of braking on the railroads of this country has been, until very recently, that of the compressed-air system.

As the speed and length of trains have increased, the braking problem has become more and more difficult of successful solution. In freight-train operation, the problem is accentuated more by the length than the increased speed and has been one more of control than of dissipation of energy. This is because maximum speeds have been restricted both by tonnage handled per locomotive unit and by the design of rolling stock used. On the other hand, length of trains has increased to such an extent, it has been difficult to transmit the braking impulse from the locomotive to 100–150 cars in such a way as to avoid undesirably variable response, rough slack action, and damage to equipment and lading. A program is now under way involving application of improved brake equipment to approximately 2,000,000 freight cars to eliminate these conditions.

In passenger equipment, the problem of braking is more affected by increased speed than increased train length. A 20-car train is about the maximum handled and most trains are further restricted by traffic requirements and station-platform limitations. The use of spring buffers and other means of either controlling or eliminating slack, simplify the problem. The use of electropneumatic brakes on unit trains effects instantaneous transmission of the braking impulse to every car. The difficulty arises from the peak speeds now encountered—100 miles per hour or more—where desired retardation rates, braking ratios, shoe pressures, and rate of energy dissipation greatly exceed past requirements for safe and economical operation.

Associated with the high-speed deceleration problem is the requirement of higher-speed operation on down grades where, in mountain territory, railroad profiles require miles of continuous operation descending two per cent grades, imposing a heavy load on the brake equipment from the standpoint of continuous energy dissipation that is almost directly proportional to the higher speed.

These problems are serious and much research and development work is being done by the air-brake manufacturers to cope with them. Tied in with these problems is the question of the deleterious effect many claim high-speed braking has on wheel life and performance. This has led to experiments with various types of nontread friction brakes.

In the urban transit field schedule speeds have also been increased with a corresponding increase in braking rates as well as acceleration. While speeds are much lower than for heavy railroad operation, the requirement for more rapid acceleration is, nevertheless, an important factor. At the same time relief from excessive heating of the wheel treads by mechanical braking is essential to economical maintenance and safe operation.

Unlike heavy railroad operations, urban vehicles rarely require braking on long grades but are concerned principally with frequent and rapid decelerations for stops. Dynamic or rheostatic braking systems and electromagnetic track brakes are now being extensively applied to urban transit vehicles.

The successful dissipation of large amounts of energy is not the only problem in high-speed braking. Due to the high retardation rates required to hold stopping distances within prescribed limits, it is desirable to take advantage without wheel sliding of all of the wheel-rail adhesion possible throughout the complete deceleration. Opposed to this, is the fact that the braking force is directly affected by many transient phenomena, which cause it to change many times during a deceleration. Not only does this make necessary the use of devices to alter the braking ratio during a maximum deceleration, but also, because these phenomena are likely to differ in magnitude on different axles in the train due to condition of wheels, shoes, brake rigging, etc., the brake application should be such as to prevent wheel sliding on the axle most susceptible to it. Devices are now being tried which anticipate wheel sliding on each axle and automatically ease the brake shoe pressure when wheel sliding is imminent.

A precept which has governed the design of new braking equipment is that improvements must be of such a nature that they will function in complete harmony with existing apparatus and thus preserve the enormous investment in equipment already in service.

The foregoing remarks give a rough idea of the magnitude and complexity of the braking problem, particularly with respect to high-speed passenger operation. The following discussion will attempt to show the part which various forms of electric braking are playing in the railroad picture and what effect they may have on the further development of means to cope successfully and economically with this increasingly difficult problem of high-speed braking.

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Braking a train from high speed to standstill usually takes the form of unproductive liberation of heat by the dissipation of kinetic energy created during acceleration. Braking on a heavy downgrade at constant speed produces the same result by dissipating potential energy created by hauling the train uphill previously. The natural function of a wheel appears to be to roll under load and not act as a medium for the dissipation of excessive amounts of energy at excessively high rates such as encountered frequently in the retardation of modern trains. Even though wheels have been employed at this task with considerable success, the demands have reached a point where other means are being considered for the dissipation of this energy.

Regenerative Electric Braking

The ideal braking system would be one which would transform into useful work all available kinetic and potential energy in the train not absorbed by normal train friction. As this would require a system of 100 per cent efficiency, it is obviously impossible but from a practical standpoint, such a system for constant-speed retardations is approached by regenerative electric braking which is available for most forms of straight electric locomotives, and is one of the several advantages which railroad electrification in general makes available.

This type of braking has been used on mountain electrifications exclusively since the benefits have been greatest in retarding heavy trains while negotiating long steep grades. Wherever used, this system has been very successful and has resulted in the following advantages:

Saving of approximately 15 per cent of total power required without regeneration, and 60 per cent on two per cent grade sections.

Elimination of brake shoe, wheel, and brake rigging trouble with attendant reduction in maintenance costs.

Smooth, continuous braking effort over long periods eliminating surges in speed with resultant wear and abuse of equipment.

Increased safety because the air brake is held in reserve so that in case of emergency stops, the air-brake system is charged and wheels and brake shoes are cool.

Increased comfort to passengers due to constant speed on grades and absence of noise due to grinding of shoes on wheels.

With this system, the braking power is limited by the driver weight of the locomotive and the capacity of the traction motors. In operation involving retardation of the train downgrade at constant speed, due to the fact the braking effort necessary is equal to the required tractive effort to haul the train up the grade minus twice the train friction, modern regenerative locomotives are capable of handling with leeway, any train downgrade which they can handle up the same grade. Grade sections also frequently include heavy curves which are fully compensated and this factor further reduces the braking necessary to hold a descending train.

Take for example a passenger train of 1,000 tons gross weight hauled by a 3,000-volt d-c locomotive recently put into service. The locomotive weighs 185 tons with 135 tons on drivers. The motoring and braking characteristics are shown in figures 1 and 2 respectively. The tractive effort required to handle this train up a two per cent grade is 47,000 pounds or 17.4 per cent adhesion, which gives a balancing speed of 50.3 miles per hour in the highest-speed motor combination. Retarding this same train down a two per cent grade requires 31,000 pounds braking effort or 11.5 per cent adhesion, which is attainable up to 67.5 miles per hour.

Track conditions, particularly curvature, will, of course, govern speeds in this type of operation, but the foregoing example shows the possibility of regenerative electric braking with a modern high-powered locomotive with respect to high-speed operation in heavy-grade territory. In this example, additional electric braking power is available if required, and with the air-brake system backing up the regenerative brake, safety is assured.

The regenerative electric brake can be used to advantage sometimes for light decelerations, the extent depending upon the grade, weight of train, and required decelerating rate. The bunching of slack and the smooth, quiet application of retarding effort is both beneficial to equipment and, in passenger service, a distinct advantage particularly to patrons in sleeping cars.

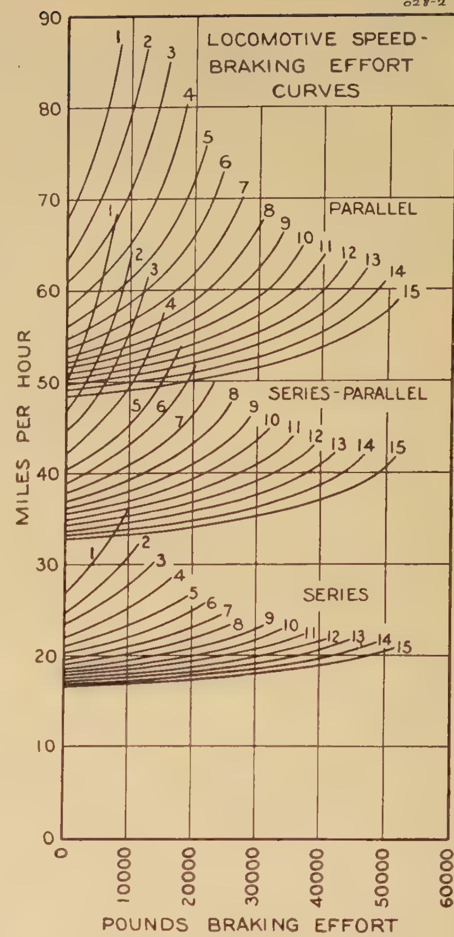

Figure 2. Speed-braking effort curves for a 185-ton six-motor electric passenger locomotive with regenerative braking

For retardation cycles approaching a full service or emergency application with air equipment, the regenerative brake, which is available on the locomotive alone, is entirely inadequate because of limitations in both driver weight and electrical capacity. For such decelerations, it is necessary to take advantage

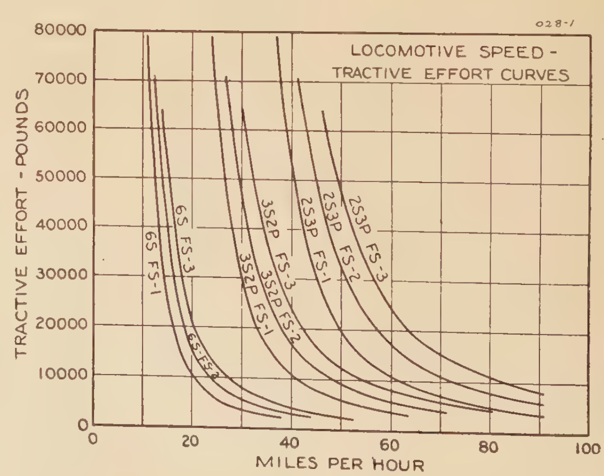

Figure 1. Speed-tractive effort curves for a 185-ton six-motor electric passenger locomotive

of the entire adhesive weight of the train. To appreciate this fully, consider the conditions involved in decelerating a 1,000-ton train from 80 miles per hour to standstill on level track.

At 80 miles per hour this train possesses a kinetic energy of approximately

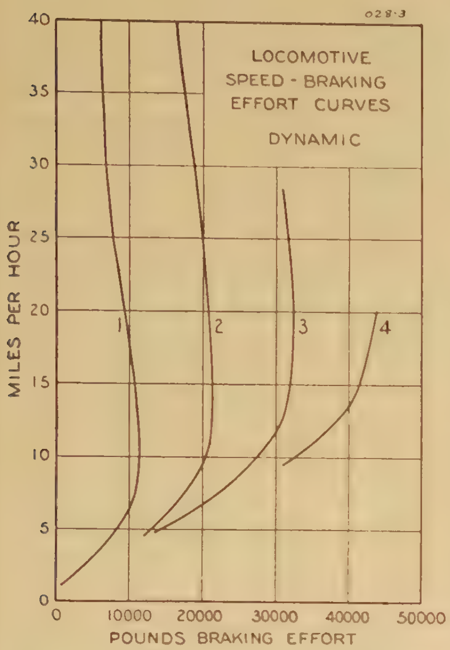

Figure 3. Speed-braking effort curves for a self-propelled locomotive with dynamic braking

428,000,000 foot-pounds, ignoring the rotational energy of wheels and axles. With a full service application of the air brakes, the deceleration will be at approximately two miles per hour per second average to standstill. On the basis of the train resistance cancelling the rotational energy during deceleration, which is essentially true, the average braking effort during the retardation cycle would be 182,000 pounds and the *average* dissipated horsepower 19,400. Taking the powerful locomotive represented by figures 1 and 2, this corresponds to a wheel-rail adhesion of 67 per cent and a braking horsepower 277 per cent of the maximum available.

In an emergency application at three miles per hour per second average deceleration, the average braking effort becomes 273,000 pounds, and the average dissipated horsepower, 29,100, corresponding to 101 per cent adhesion and 415 per cent of the maximum available braking horsepower of the locomotive.

These decelerations, which are not based on unusually severe conditions of either maximum speed or weight, give another insight into the magnitude of the energy to be dissipated and the resulting forces involved in the braking of high-speed modern trains.

Dynamic Electric Braking

Self-propelled locomotives using electric drive such as the Diesel-electric and steam-electric types can be equipped with dynamic braking which does not differ essentially from regenerative electric braking except that the energy must be dissipated in some manner on the locomotive rather than returned to the distribution system.

In some respects the dynamic electric brake has advantages the d-c regenerative brake does not have, in that the dynamic brake is flexible as to its characteristics. There are two types of braking characteristics, the holding brake and the stopping brake. The former has variable braking effort at constant speed and the latter, constant braking effort at variable speed. The regenerative electric brake on d-c equipment is of the holding-brake type inherently because it is tied down to constant voltage operation. The dynamic electric brake, however, can be designed to produce any desired characteristic by suitable arrangement of circuits, excitation, and external resistor values.

Figure 2 shows the characteristic curves of the regenerative electric brake on a d-c locomotive. The relatively flat shape means the locomotive can descend a variable profile at practically constant speed, automatically adapting itself to the changes in braking effort required.

Figure 3 shows a dynamic braking characteristic that is vertical and ideal for applying constant braking effort automatically throughout a deceleration. This can be approached with the regenerative brake in figure 2, but only by a skilled operator through constant manipulation of the braking controller, including shifting the motor combinations when required.

The 5,000-horsepower steam-electric locomotive built for the Union Pacific system, has a unique application of dynamic electric braking (figure 4). The unusual feature is the method of dissipation of electric energy generated during braking. The energy is delivered to a resistor consisting of sections of seamless stainless-steel tubing, through which water is circulated from the main power plant, the water being heated and in heavy braking duty partially converted into steam. The outlet of the resistor is connected to a separator from which hot water is returned to the hot well and steam to the main condenser.

The electric brake may be used alone or in conjunction with the air brakes. When used alone or with the air brake up to 48 pounds brake-cylinder pressure, the output is limited automatically to 4,800 kw to protect the motors from continuous overload down long mountain grades. From 48 to 100 pounds brake-cylinder pressure, indicating a stop is imminent and the demand for power limited in time, the output of the electric brake is graduated automatically up to 7,200 kw at the 100-pound cylinder pressure which corresponds to an emergency application on a modern electro-pneumatic straight air equipment as used on streamlined trains.

To date there have been no applications of dynamic braking to Diesel-electric locomotives in main-line service, although there is no reason why such braking cannot be applied. Experience with this type of braking on the Union Pacific steam-electric locomotive has emphasized the advantages of the system in retardations at constant speed or moderate decelerations, as well as safety at higher speeds in downgrade operation.

On a Diesel-electric the energy can be absorbed in resistors and the heat ultimately released to atmosphere through a system utilizing the engine cooling water and radiators. As alternatives, air-blast resistors might be used or resistors cooled by a separate fluid system employing a synthetic liquid of desirable characteristics with respect to specific

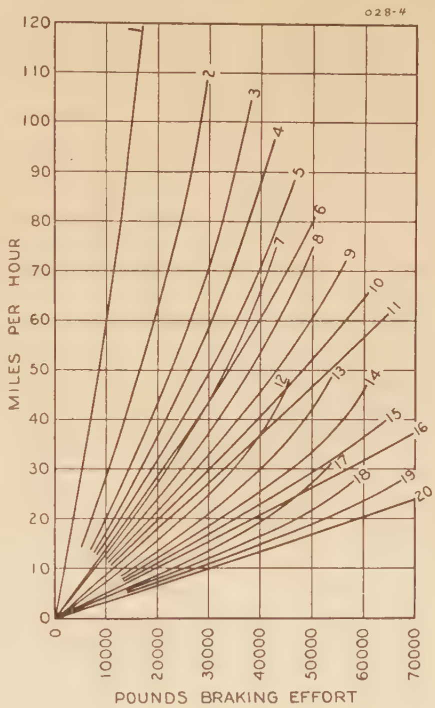

Figure 4. Speed-braking effort curves for 5,000-horsepower steam-electric locomotive (dynamic braking)

heat, boiling and freezing points, dielectric strength, inflammability, etc.

A miniature edition of such a dynamic brake was put in service recently on a 400-horsepower 20-ton Diesel-electric rack-rail locomotive for pushing a 12-ton observation car up and retarding it down the Manitou & Pikes Peak Railway which negotiates Pikes Peak in Colorado. The braking problem on this nine-mile road is severe because the average grade is 16 per cent and the maximum 25 per cent and absolute reliability is essential. The use of dynamic braking, in which power is dissipated in air-cooled resistors in the locomotive allows full control of the speed throughout the descent with the dynamic brake alone except at stopping when this brake fades out.

The use of an electric brake would eliminate immediately all problems arising from sliding-friction phenomena, wheel slipping, and temperature changes in shoes. Because of its prompter action, fewer variable characteristics, and flexibility, it is effective more quickly than the air brake and can be used as well to assist the conventional brakes where high-speed demands exceed their capacity.

Electric braking so far has hardly been tried in the streamliner field where speed is the outstanding factor. Today we hear 100 miles per hour talked of freely as a normal nominal top speed just as 60 miles per hour was commonly referred to as a measuring stick of high speed a few years ago. Tomorrow 100 miles per hour maximum on the rails may well be common, and we shall be looking at higher speed levels again as indicative of the trend of ultramodern railroad equipment. Even today, the modern self-propelled locomotive with electric drive is geared for a peak speed of 120 miles per hour. As these top speeds increase, the braking problem becomes more and more acute. The kinetic energy in a train at 140 miles per hour is about double that in the same train at 100 miles per hour. As this trend to higher speeds develops, the necessity for new braking methods will become increasingly pronounced. The electric brake is a potential candidate to meet this necessity; in fact, it may open the door to ultrahigh-speed operation, for without suitable braking equipment, such operation is impractical.

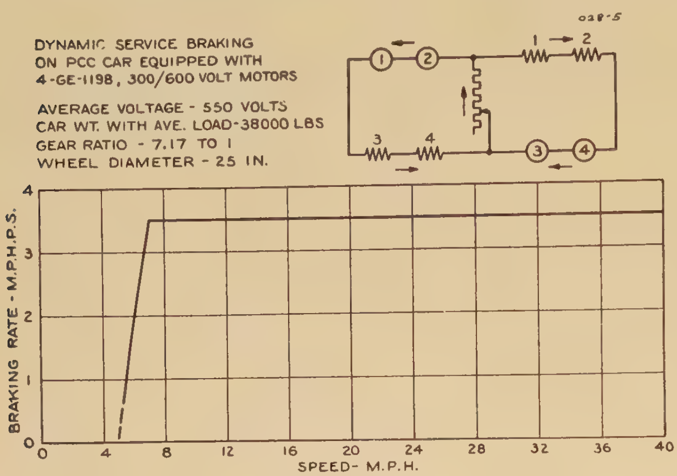

Figure 5. Dynamic service braking curve for PCC car

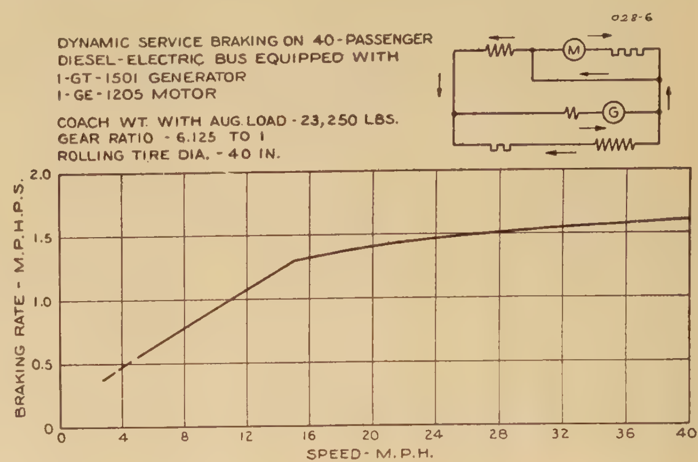

Figure 6. Dynamic service braking curve for Diesel-electric bus

Electric Braking in Urban Transit Service

In recent years, electric braking also has been used in urban transit service, which is quite different from heavy main-line railroad operation. Urban service involves relatively light vehicles, such as the Electric Railway Presidents' Conference Committee or "PCC" car, the single-motor trolley coach, and the gas-electric or Diesel-electric bus.

The PCC car utilizes entirely new propulsion equipment to obtain high rates of acceleration and braking, and resilient wheels which have rubber inserts between the wheel tire and hub to reduce wheel and rail noise. This design was a factor in the adoption of a braking system comprised of dynamic braking, magnetic track brakes, and conventional air-operated wheel brakes properly blended by a single brake pedal.

During a typical service stop of a PCC car weighing approximately 38,000 pounds with seated load and decelerating at $4^3/_4$ miles per hour per second, the traction motors contribute $3^1/_2$ miles per hour per second of dynamic braking and the magnetic track brakes $1^1/_4$ miles per hour per second deceleration from 40 miles per hour down to approximately 7 miles per hour. At this speed the dynamic braking fades out rapidly and the air brakes are automatically engaged to assist the magnetic track brakes in maintaining the braking rate to standstill. A feature of this braking sequence is the fact that the air brakes are called for at the same pedal by which dynamic braking is established, but the air brakes are held off automatically so long as the dynamic braking builds up to the desired rate. Thus, if the dynamic brakes should fail to build up for any reason, the air brakes would be available immediately to assist the magnetic track brakes in braking the car. Emergency stops at a rate of 7 to 8 miles per hour per second are obtained by increasing the dynamic braking to 4 miles per hour per second and the magnetic track brakes to 3 or 4 miles per hour per second deceleration, by depressing the brake pedal to its lowest position. An infinite number of intermediate braking rates between one mile per hour per second and emergency rate are available by depressing the brake pedal a corresponding amount.

Dynamic braking was selected as the primary brake on PCC cars because it is entirely independent of the trolley power in case of dewirement and because it requires relatively little control equipment in addition to the accelerating control, much of which is also used during the braking cycle. In addition, an emergency dynamic braking position is provided on the manually operated motor reverser. When the reverser is placed in this position, the traction motors are short-circuited to provide a very effective

dynamic emergency brake if all other brakes should fail.

Each magnetic track brake consists of a large electromagnet mounted on a long, narrow shoe that is suspended parallel to and directly over the rail between the two wheels on each side of each truck. Four such magnet shoes are mounted on a car. When the electromagnet coil is energized, the shoe is pulled against the rail by its own magnetic action and the resultant friction of the brake shoe on the rail exerts a braking effort on the car. The relative effect of this retarding force is dependent upon the magnetic strength of the electromagnet coil, which is controlled by depressing the brake pedal. The track-brake coils are energized from a storage battery in order to make this brake also independent of the trolley power in case of dewirement. This brake is not usually cut off before standstill is reached, nor does it fade out at low speeds. However, provision is made to release it when the brake pedal is latched down to continuously engage the air brakes for prolonged parking, in order to eliminate needless drain of energy from the battery.

The use of electric braking as the primary brake on PCC cars eliminated the problem of using air-operated wheel brakes for service stops at high rates of deceleration with the attendant dissipation of large amounts of heat in the car wheels. In fact, some of the newest cars use a spring-applied clasp brake to supplement the electric brakes at low speeds and for parking, and thus eliminate entirely the use of air-operated wheel brakes. The same principles of electric braking utilized so successfully on PCC cars have recently been applied and have materially simplified the problems of equalization and prompt response of braking effort on all axles of a multisection subway-elevated train (figures 5 and 6).

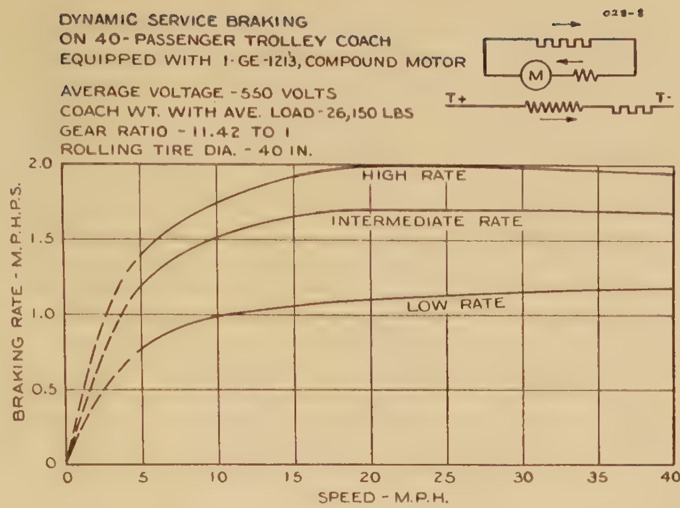

Figure 8. Dynamic service braking curve for single-compound-motor trolley coach

Electrically propelled automotive-type urban transit vehicles, particularly the trolley coach, have presented a more serious braking problem than mechanically driven busses, due to the higher rates of acceleration and deceleration demanded from electric drive and due to the free-wheeling characteristic of electric drive in which there is no engine compression to assist the wheel brakes. The use of higher ratios (power-to-weight) with electric drive in the last few years, coupled with the fact that the physical size of wheel brakes has reached practical limits, led to the introduction of the compound-wound trolley-coach motor and automatic control equipment designed especially for regenerative and dynamic braking and speed control, and to the development of new series-wound motors and control equipments designed especially for dynamic braking.

It is characteristic of the compound-wound motor that, if the shunt-field strength is increased while motoring at a given speed, the motor, driven by the inertia of the load, begins to regenerate and exert a braking effort on the load until a lower balancing speed corresponding to the stronger shunt-field strength is attained, at the same time returning power to the line.

This principle of shunt-field control is utilized with the modern compound-wound trolley-coach motor to provide a number of balancing speeds over the upper half of the vehicle's speed range, with regenerative braking automatically obtained during deceleration from one balancing speed to another or while holding the coach at any one of these balancing speeds during descent of a grade.

The compound-wound motor with the shunt-field winding separately excited from the trolley has ideal characteristics for dynamic braking (figure 8). By opposing the series and shunt fields, a differential action is obtained which prevents the imposition of excessive strains on the rear axle or gearing. Dynamic braking and air braking are applied by a single pedal. Maximum dynamic braking is obtained at approximately one-half pedal travel; and at the same time a small amount of air is admitted to the brake cylinders. Further movement of the pedal maintains maximum dynamic braking until approximately 85 per cent of the air braking is being applied. Dynamic braking is then reduced to the minimum and 100 per cent air braking applied. This operating sequence permits maximum utilization of dynamic braking without applying excessive braking to the rear wheels during an emergency stop.

Paralleling the development of the compound-wound motor is a new series-wound motor for trolley coaches which has been designed especially for dynamic braking. This development was made possible largely by the introduction of a practical, automatic acceleration control which has been adapted for use during dynamic braking automatically to commutate the braking resistance in series with the motor to hold the desired ac-

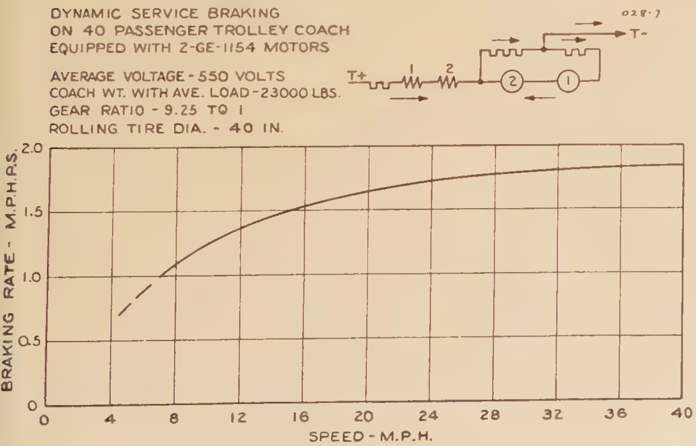

Figure 7. Dynamic service braking curve for two-motor trolley coach

celeration rate. An infinite number of intermediate braking rates between the minimum and the maximum are available merely by depressing the brake pedal a corresponding amount. The same brake pedal also controls the air brakes, which may be applied simultaneously with the dynamic braking to provide higher braking rates than are possible with dynamic braking alone, or to assume the braking duty at low speeds below which the dynamic braking automatically fades out.

The past year or two has also advanced the application of electric service braking to existing cars and trolley coaches of older design. The scheme most universally employed for this purpose consists essentially of connecting load resistors across the motor armatures and connecting the armatures in series with the motor fields in such a manner that, when the fields are excited from the trolley, the generated voltage of the motor armatures opposes the applied trolley voltage. This connection results in a differential action which automatically increases the field strength as the armature voltage decreases with vehicle speed in order to maintain a substantially constant rate of deceleration over a wide vehicle speed range. This form of dynamic braking is advantageously applied to older-type cars and trolley coaches having nonautomatic control and excess motor capacity.

Dynamic electric holding brakes were practically standard equipment on the earliest gas-electric busses with dual-motor drive, as these busses had only two-wheel mechanical brakes. However, the holding brake as applied to these vehicles was not designed to assist the wheel brakes during a service stop, but was intended merely for holding the bus at a predetermined speed on some specific grade. Since the introduction of the modern single-motor equipment for gas-electric or Diesel-electric busses was subsequent to the universal adoption of four-wheel air brakes for railless urban vehicles, the dynamic holding brake has been retained only where unusually long or severe grades are encountered, complete reliance being placed on the air brakes in most cases.

However, increased size of busses and installation of larger engines, as well as a demand for higher schedule speeds, have recently promoted the development of a fully automatic electric service brake to supplement the air brakes on modern gas-electric and Diesel-electric busses. This form of dynamic braking utilizes power obtained from the main generator to excite the fields of the traction motor, the armature of which has a braking resistor connected across it. The amount of motor field excitation taken from the generator is automatically regulated to maintain an approximately constant braking rate over the entire speed range of the bus. The electric braking may be applied whenever the engine throttle is returned to its idling position, in order to simulate the retardation effect of engine compression, or it may be applied by initial movement of the brake pedal. It is automatically cut off at low bus speeds. Test installations indicate a material improvement in the life and maintenance of the wheel brakes on Diesel-electric busses equipped with this type of dynamic service brake.

In all cases where modern electric service braking has been applied to supplement wheel brakes, the life and maintenance of the wheel brakes on electrically propelled vehicles has been equal to or better than the life and maintenance of wheel brakes on similar mechanically-driven equipment, in spite of the higher schedule speeds and higher deceleration rates normally used on electrically-propelled vehicles. The use of higher rates of electric braking on trolley coaches and on electrically-driven busses is not recommended, however, because the braking must all be done on the rear axle and would thus cause the rear wheels to assume a very major portion of the total braking duty. This would cause the vehicle braking characteristics to approach the obsolete performance standards of two-wheel brakes which, for obvious reasons, the industry saw fit to discard years ago.

Conclusions

Operating experience in recent years clearly establishes the importance of electric braking as a supplementary system both in heavy railroad operation and for urban transit. A continued demand for higher speeds is to be expected and the limitations of mechanical brakes without excessive weights and costs have already been indicated. Thus, electric braking may easily augment the increasingly drastic requirements of electric modern motive power.

Of the several types of electric brakes discussed, regenerative braking is available for electrified railroads or trolley-coach lines while dynamic or rheostatic brakes, eddy-current brakes, and magnetic track brakes can be applied as well to self-propelled vehicles. Under heavy braking conditions, regeneration returns appreciable amounts of power to the line. Exceptionally favorable conditions such as a three per cent continuous grade may return regenerated power amounting to as much as 70 per cent of that used for motoring.

Dynamic braking delivers electrical energy to resistors where it is dissipated in the form of heat. Eddy-current brakes accomplish the same result by use of a self-contained independent device attached to the motor frame and coupled to the armature shaft. Eddy-current brakes are operating successfully on rapid transit equipment but in general the extra cost discourages their general use. Dynamic brakes on the other hand make use of the existing motor as a generator and usually the resistor equipment normally used for acceleration.

Magnetic track brakes while simple and comparatively inexpensive are only justified where rapid and frequent decelerations are absolutely essential to the performance of a given schedule. Present applications are limited to PCC cars and rapid transit trains.

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Discussion

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Network Coupling by Means of Static Electronic Frequency Changers

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DURING the last few years several attempts have been made, especially by some foreign railways, to find ways and means to feed their 11,000-volt $16^2/_3$-cycle railway trolley system directly from a commercial 50-cycle power source by means of a simple device, or then to have the locomotives equipped with such apparatus which would permit using power at the latter frequency fed directly to the trolley line. In other words, it was felt that many advantages could be gained if the trolley line could be fed, directly, or over a simple converter, from any commercial power network which would be adjacent to the railroad's right of way. This desire led to the development of the 50-cycle series commutator motor by the Siemens Schuckert Company, a 50-cycle converter cascade motor by the Krupp Company, and to the converter locomotive by Von Kando. It also led to the design by several companies in Europe of a locomotive with a built-in mercury-arc rectifier for converting the 50-cycle power fed directly to the trolley line into direct current suitable for standard railway motors.

Furthermore, studies were made using a commutatorless motor with a mercury-arc rectifier. The development of this motor, having no commutator but using a rectifier for commutation and able to operate on commercial frequency, was, however, abandoned in its early stages, as far as its use on a locomotive went. However, it may be said that since single-anode tank rectifiers of large capacity are now available, a more economical connection for the commutatorless motor could be employed than was considered when the first investigations were made.

The operation of these various systems proved successful from a technical point of view, but they were found less advantageous from an economical and maintenance standpoint.

At this time, as briefly referred to above, still another system permitting the use of power of conventional frequency was under careful consideration, namely, using a rectifier on the locomotive converting 50-cycle power fed directly to the trolley system into direct current and supplying it to standard railway motors. Finally four locomotives of this design were built. Three of them are operating on the Hoellental railroad system. This system was originally projected for a trolley voltage of 15 kv but had to be raised to 20 kv in order to compensate for the high inductive drop at 50 cycles. The locomotives were equipped with standard series motors, a rectifier and transformer, and devices for voltage control, etc. The 50-cycle power supplied to the trolley system from a conveniently available power line is stepped down and converted into direct current by the transformer and rectifier on the locomotive.

However, before the studies undertaken by four companies in connection with these locomotives were very far advanced, it was found that the grid control, which at first thought appeared extremely simple, became quite involved. One company even abandoned the idea of controlling the voltage by means of grids and introduced tap changing under load equipment for regulating the anode voltage of the rectifier, and thus in turn the direct voltage supplied to the motor.

Simultaneously with this development, attempts were made to develop a static frequency changer using grid-controlled mercury-arc rectifier-inverters (electronic rectifier-inverters). This method would also make it possible to take power from any commercial network, convert it and feed the trolley system with a frequency suitable for a-c railway motors.[1–5] Such devices would be static and some of them would permit flexible coupling between a three-phase 60-cycle, and, for instance, single-phase 25-cycle trolley systems. Tests[6] with such frequency changers were started over six years ago, and after extensive experiments with sets of a capacity of 500 to 1,000 kw, a commercial installation was finally erected near Basel, Switzerland, feeding power into the $16^2/_3$-cycle trolley system of the Wiesenthal Railroad, Germany, from a 50-cycle network.[8,17,19]

The object of this paper is to discuss such methods of frequency changing using electronic rectifier-inverters which would make it possible to transform three-phase power of 60 or 50 cycles into 25 cycles, the frequency commonly used by the railroads in the United States. The other systems as used today in Europe are briefly referred to and discussed only where they have a bearing on the systems suitable for obtaining 25-cycle power.

Rotating Versus Static Frequency Changers

The phenomena taking place during conversion of electric energy from one frequency to another will be discussed briefly in order that the arguments in favor of methods using electronic converters can be easily followed, and so that some of the theoretical considerations put forward in several articles referred to below can be fully appreciated.

We may recall the fact that the energy furnished by a three-phase network, with a symmetrical three-phase voltage system, normally supplies a constant power flow in spite of the fact that in each individual phase the voltage and current change according to a sine wave. Power from a single-phase network, however, pulsates with twice the frequency of the induced voltage and current, which, as is well known, is an inherent characteristic of such systems. The instantaneous power demands of the two systems are not equal. Therefore, the supply of power from a network of commercial frequency to a single-phase railway system, necessitating conversion of energy from 60 to 25 cycles, means the electrical coupling of two power systems, each of which has quite a different characteristic of its natural flow of energy.[9]

Let us first analyze the power relation in case a three-phase single-phase motor generator set is used for coupling such systems. The power absorbed by the motor from the three-phase 60-cycle system shall be assumed to be constant and is illustrated by T in figure 1*b*. T is the summation of the power furnished by each phase X, Y, W, of the three-phase system. The power demand of the single-phase network on the three-phase network is shown in figure 1 by curve S, which in case of a mechanical frequency changer will always be active. In other words, in such a frequency changer no reactive power can be transmitted from one to the other system, and the same condition holds true

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1. For all numbered references, see list at end of paper.

for a circuit as shown in figure 2. From figure 1*a* it can be seen that the single-phase energy S pulsates about a mean value T with a frequency equal to twice that of the frequency of the current i and voltage e of this system. The mean power of the single-phase system must be equal to T as the loads of the two machines average the same over one cycle, but, as said above, are not the same at each instant of the cycle. It will therefore be seen that during certain intervals (*a*), for instance, single-phase energy equal to the horizontal hatched area will have to be supplied from a source other than the three-phase system, while during the intervals (*b*), the same amount of energy has to be absorbed and stored in some way or other in order that the three-phase energy supply may be constant (equal to T). In other words an energy reservoir will be necessary to balance the available and required power. Curve S_1 shows, for a few cycles, the magnitude of energy which has to be taken care of at each instant by certain means (accumulators) capable of absorbing and freeing energy.

In the case of a motor generator set the rotating masses will automatically take care of the excess energy during period (*b*) and release it during period (*a*). However, it must be realized that this will only take place if the speed varies or deviates from the mean value N as shown in curve

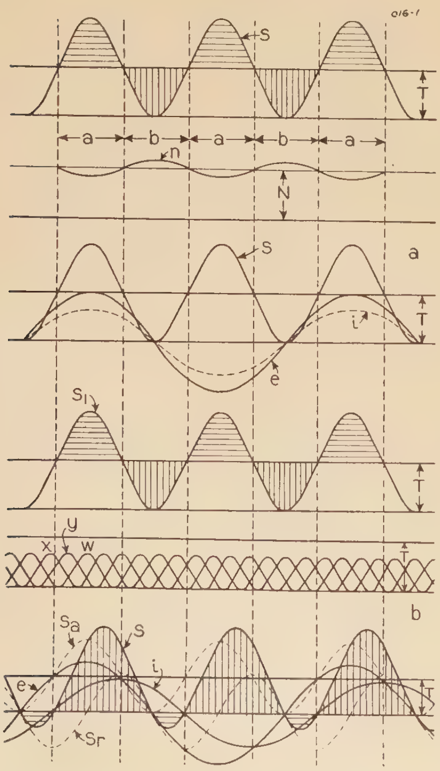


Figure 1. Energy relation between three-phase, single-phase systems of frequency converters

n (figure 1*a*). In other words, during the interval (*a*), the speed of the rotating masses is being advanced, while during interval (*b*) the speed will decrease over the mean value N.

Therefore, a rotating frequency changer (motor generator set) is able, with its normally inherent rotating masses, to take care of the surplus, or lack, of energy as compared to the mean value T, since the rotating masses permit storing and supplying energy. The three-phase motor will, therefore, draw constant energy from the 60-cycle network in spite of the pulsating character of the single-phase load, but the speed will fluctuate slightly with the frequency of the pulsating single-phase load.

The power supply for conversion of three-phase to single-phase current by means of an electrically controlled rectifier-inverter is illustrated in figure 1*b*. The power demand S oscillates at twice the single-phase frequency as above, T being the mean value and S_a the active and S_r the reactive component of power demand from the single-phase supply. Both were taken to be equal, representing a power factor of approximately 0.7. In the case of a frequency changer using an electrically controlled rectifier-inverter, no inherent means are available to permit storing and releasing of power at the frequency impressed by the single-phase load characteristic. Therefore, with such equipment the power oscillations are transferred to the three-phase network, which will be loaded with currents departing from sine waves and of frequencies foreign to the network frequency. This will result in an increase in reactive power, harmonics, and a negative component in the three-phase current system which will in turn affect the efficiency factor.

The above condition can only be corrected if means are used to take care of the differences between the instantaneous power demands of the systems as is done inherently in the case of a mechanical frequency changer. Such energy-storing equipment can be built up using a battery of capacitors and reactors (a resonant circuit). However, due to the fact that the intermediate d-c circuit of such an electronic converter, see figures 3 and 4, has a superimposed alternating current of 360 cycles (if a 6-phase electronic converter is used) and 720 cycles (if 12 phases are used), the smoothing or storing equipment may have to be of fairly high capacity. The use of capacitors and reactors forming a resonant circuit, even if of large capacity, introduces very little additional losses, as the energy can be kept oscillating between capacitors and reactors, consuming very little power. In case it is found advisable that the single-phase power energy oscillations may partly be transmitted back to the three-phase system, in other words, if T may vary, then the capacity for the storing equipment (capacitors and reactors) becomes relatively small. However, due to the recent developments of static capacitors for power-factor-improving equipment, the cost of such storing equipment is no longer prohibitive, and enough capacity may be provided to obtain a constant energy flow from the three-phase network as shown by T.

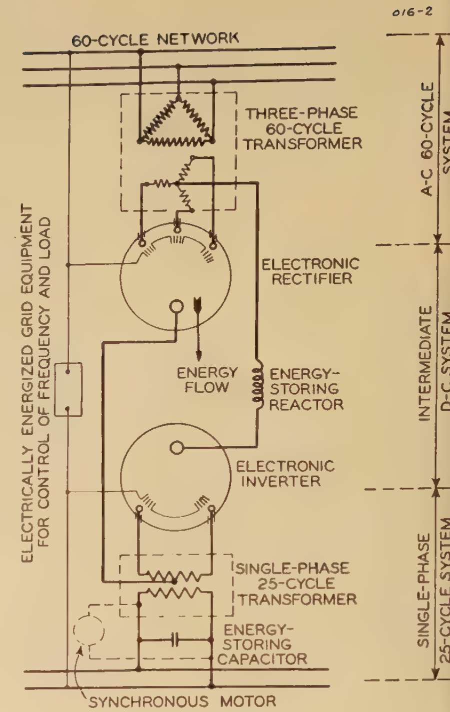


Figure 2. Fundamental circuit diagram for an electronic frequency converter with intermediate d-c step

Electronic Frequency Changer With Intermediate D-C Step

Flexible Indirect Coupling Between Systems

The simplest method for effecting a flexible coupling of a-c systems of different frequencies by means of electronic rectifiers and inverters is shown in figure 2. This system consists of a rectifier, a reactor, and an inverter. Three functions are necessary: First, the a-c power of 60 cycles is rectified into d-c power; second, the d-c power is inverted into 25-cycle single-phase power, and third, the difference between the instantaneous power demand of the single-phase system and the three-phase supply has to be balanced by an energy accumulator, which may consist of a reactor and a capacitor. The reactor

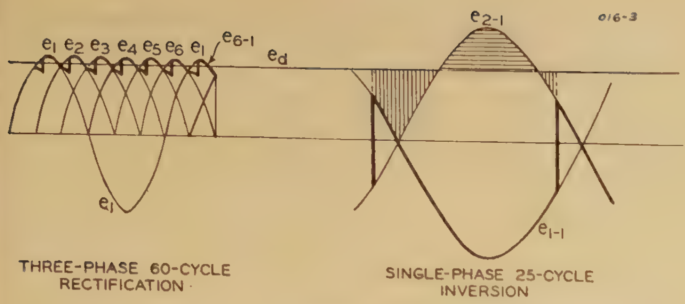


Figure 3. Relationship between single-phase voltage and intermediate direct voltage obtained from six-phase system

e_1, e_2, e_3, e_4, e_5, e_6, e_1, etc., represent phase voltages of the 60-cycle six-phase system. e_{1-1} and e_{2-1} represent voltage waves of the 25-cycle single-phase full-wave system. e_d represents the intermediate direct voltage of the rectifier inverter

is inserted between the rectifier and inverter, and takes care of the differences of the direct voltages e_{6-1} and e_{2-1}, figure 3. The voltages e_{6-1} and e_{2-1} refer to a six-phase rectifier system and a single-phase inverter system. For further data on rectifier and inverter operation, see bibliography.[13,14,25,26] The above arrangement does not allow reactive power to be fed back to the three-phase system, and only active energy can be transferred from the three-phase to the single-phase network. The reactive power would therefore have to be taken care of by a static or a synchronous condenser connected to the single-phase system.

The first two steps, namely, converting power from alternating current to direct current and from direct current to alternating current, have been done separately in many installations during the last few years and a great deal of experience was recently gained during extensive field as well as factory tests in connection with inversion of direct current to alternating current by means of grid-controlled rectifiers.[11,21,23] These tests have demonstrated that the flexibility between two a-c networks is fully maintained and no instability resulted no matter how large and sudden a change in frequency took place.

It may therefore be realized that at this time a frequency-changing set of great reliability can be built by utilizing the experience gained in some of the high-voltage rectifier and inverter installations briefly referred to later on.

Electronic Frequency Changer Without Intermediate D-C Step

(a). Flexible or Rigid Direct Coupling of Systems

The converter referred to above could be built up by using either single-anode or multianode tank rectifier and inverter; the one discussed below necessitates the single-anode tank arrangement. Figure 4 shows the basic circuit diagram of such equipment, consisting of a transformer and 12 single-anode grid-controlled rectifier-inverters; one set having their cathodes and the other set their anodes connected to one side of the single-phase system. Each pair of tanks connected to the same secondary winding constitutes a switch, in other words they permit current to flow in either direction. Let us assume that the grids of tubes R_1 permit current to flow while all other anodes are blocked, then the transformer winding 1 is connected to the single-phase system. After a certain period this set of tubes is blocked and set R_2 is released, thus phase 2 of the transformer may supply current. After another period of time the next phase, 3, is brought into play, and then 4, 5, etc. Figure 5 shows the voltage of each phase, and below the arc current which is commutated from each anode to the anode of the succeeding phase as the impressed alternating voltage of this phase becomes more positive than that of the phase carrying the arc. It would have to be arranged, therefore, that the grid-control equipment permits the flow of current according to the time interval t_1 to t_{14}. This results in sections of voltages e_1 to e_6 being made available and joined to the heavy-line curve which becomes the voltage e_s of the single-phase system. The flow of current through the individual tubes can be seen from the second curve of figure 5 for the case where the single-phase voltage and current are in phase.

The frequency ratio between e_1 to e_6 and e_s as shown in figure 5, upper curve, is about 3:1. However, as can be seen from the voltage curves below, any frequency ratio may be obtained, as any number of sections e_1 to e_6, or e_1 to e_6+e_1, or e_1 to $e_6+e_1+e_2$, etc., of the transformer phase voltages can be built up to produce the

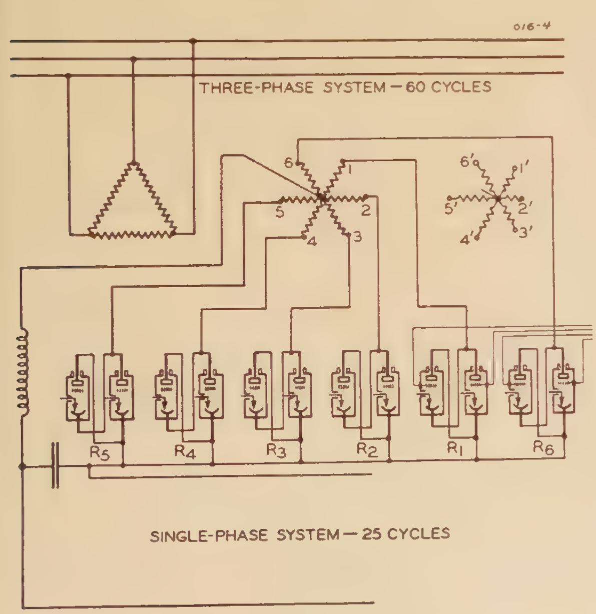


Figure 4 (left). Fundamental circuit diagram of an electronic frequency converter

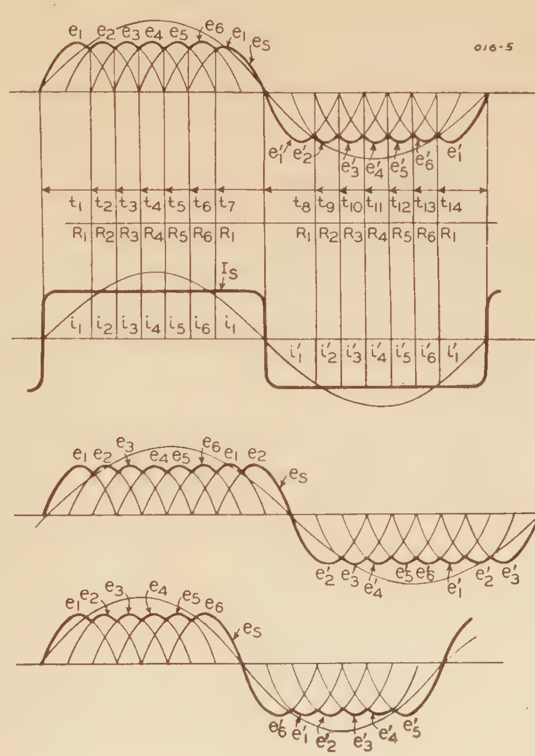


Figure 5 (right). Formation of single-phase voltage and current waves for different frequency ratios in an electronic frequency converter

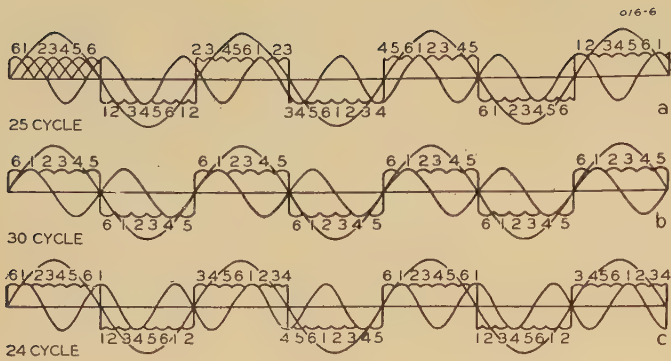


Figure 6. Diagram showing the firing of anodes for various frequency ratios in a flexible frequency converter

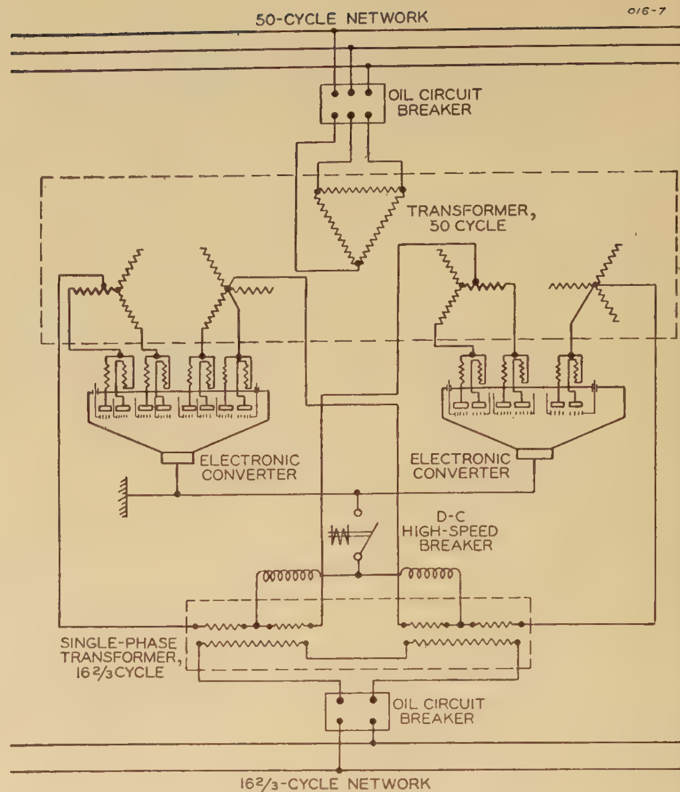


Figure 7. Fundamental circuit diagram for a rigid frequency converter

desired single-phase voltage e_s. A further consideration of these curves will show also that a change in the frequency of the three-phase voltage still permits obtaining a constant single-phase frequency. The flexibility of this type of frequency changer with electronic equipment will be analyzed still further below using figure 6.

As is well known the firing of the anodes can be controlled by means of grids in such rectifier tubes and therefore the voltage curve e_s in figure 5 could be made to resemble more closely a sine wave by retarding or accelerating the firing of some of the anodes.

The scheme[3,4] of employing a transformer with a modified secondary winding (see figure 4, system 1′, 2′, 3′, 4′, 5′, 6′) cannot be used unless the ratio of the frequencies is for instance 3:1, as is the case in Europe between the conventional 50-cycle power and the $16^2/_3$-cycle railway systems. Furthermore, this permits only a rigid coupling between the two systems. For these reasons no further consideration will be given to these methods in this paper.

Analyzing still further the arrangement shown in figure 4 of frequency conversion, it is quite apparent that this type of equipment and others which will be discussed later do provide a completely flexible coupling between two systems. For the sake of brevity no detailed consideration is given in this discussion to the subject of commutation between sections of a rectifier system nor to the influence upon commutation in case a potential is impressed upon the single-phase system by other converters. However, an analysis of conditions caused by various ratios of the three-phase to single-phase frequencies is given below for purpose of determining the duty imposed upon the individual anodes.

Part *a* of figure 6 shows the condition existing when the frequency ratio is 60 to 25. The commutation of current between the two rectifier systems can be effected at any instant by means of the grid-control equipment.

Part *b* illustrates the condition when the frequency ratio is 60 to 30. Here we see that each of the six anodes fires only once during the active period of either system; further, we also see that the same anodes bear the entire burden of each commutation, and each of the others always carried the current during the same part of the active cycle of its system. From this it is obvious that the duty on the anodes within one of the systems cannot be equally distributed, and the anode subjected to the most severe duty will govern the rating of the rectifier.

Part *c* indicates the relationship existing when the frequency ratio is 60 to 24. Conditions in this instance are more favorable than for the ratio of 60 to 30, but it does have some undesirable characteristics. Investigation shows that the burden of commutation is now divided equally among four of the six anodes employed in each system, and although this does limit the capacity of the rectifier to some value less than it would have if used only for rectification, the reduction in this case is less than for the frequency ratio of 60 to 30.

From the above discussion of the unusual frequency ratios it may at first appear that the ratio of 60 to 25 is very near to the undesirable condition of loading of anodes encountered when it approaches 60 to 24. However, before drawing definite conclusions it might be well to recall the reason for developing such apparatus; that the coupling be entirely flexible, that is, that the frequency ratio may be a variable. With this in mind let us consider what determines the frequency of the two systems; in the case of the three-phase system it is without exception dependent upon the speed of the prime movers driving the generators, while the single-phase system may or may not include rotating equipment. The three-phase systems are well known to maintain a constant frequency; on the other hand, traction systems do allow relatively large variations, the reason being that if compared to the supply capacity, great power demand fluctuation occurs. In the case where no rotating equipment is supplying energy to the single-phase system, its frequency will be a function not only of the active power requirements, but also of the reactive power demand as well. In either case, the single-phase frequency is subject to relatively wide fluctuations.

The fact that the frequency ratio is a variable eliminates the possibility that the unit will be subject to sustained undesirable operating conditions.

Furthermore, from part *b* of figure 6 it may be concluded that the conversion of power from a 50-cycle to a $16^2/_3$-cycle system (3:1) does not provide a favorable utilization of the rectifier-inverter and it may be concluded from the above consideration that more favorable operation may be obtained when 60-cycle power is converted into 25-cycle power, since the anodes are subjected to a lower duty during commutation.

(b). Rigid Indirect Coupling of Systems

Figure 7 shows the diagram of connections of such a type of frequency changer with the electronic converters and the three-phase and single-phase transformers. This system has, however, a serious inherent disadvantage—namely, the coupling is not flexible and therefore any change in frequency on one system will automatically affect the frequency of the other. However, in spite of this drawback such equipment has been installed to supply a small railroad with $16^2/_3$-cycle current. The set is rated 3,600 kva continuous load, 2,520 kw (power factor 0.7) 4,000 kva one-half hour, and 6,000 kva, one minute, and has been in commercial operation since December 1936. The unit furnished the entire load for over a year for this branch railroad which was up to then supplied by means of two motor generator sets, each rated 2,100 kva. Therefore, these two motor generator sets were used only for standby units, but it was contemplated to have one working in parallel with the static frequency changer as soon as this method of conversion has proved satisfactory and could then be reconnected in such a way that it could work in parallel with any other converter, whether of the mechanical or another electronic type. The original setup as indicated above was such that the frequency of the single-phase output was a function of the frequency of the three-phase supply system. In other words, the coupling of this system as originally used was not flexible and parallel operation of different units could not be accomplished without using a connection similar to the one which will be explained below. The frequency changer was supplied by a 45-kv 50-cycle transmission line, and therefore the rectifier transformer was provided with a 45-kv delta primary winding. The voltage of the intermediate d-c system of the frequency changer was chosen at 2,000 volts and does not depend upon the voltage of either the three-phase or the single-phase network.[8,17,18,19,20]

The grid control of this unit is such that a slight inaccuracy in the adjustment of the firing period may make the unit completely inoperative. Furthermore, this method of frequency changing is very limited, as stated before, as it does not provide a flexible coupling, produces an unequal loading of the anodes, and necessitates a tank with an abnormal number of anodes. The advantages which may be stressed are long firing time of the anodes, and the possibility of furnishing wattless power from one network to the other.

Two things, however, were definitely demonstrated by the installation of this type of static frequency changer, namely, that it requires less space and has less weight, both of which reduce the cost of the building and foundations. Furthermore, the efficiency at light load was considerably higher than the one which could be obtained with a mechanical converter.

It may be mentioned that right from the beginning considerable difficulties were experienced due to the fact that the communication systems were exposed to the trolley, as well as feeder system, both of which showed considerable current and voltage wave distortion from the rectifier-inverter. This situation was corrected by means of filters. Further on will be outlined some schemes and methods which may be employed in order that the inductive co-ordination of power and telephone systems may be obtained for large installations of static frequency changers without using filters.

(c). Flexible Indirect Coupling Between Systems

The static frequency changer discussed below has recently been perfected and is based on a somewhat different principle than the arrangements described above. It attracted considerable attention among European engineers, especially due to the fact that it permits flexible coupling of two a-c systems of any frequency, without appreciable distortion of the current and voltage waves. Such a frequency changer was recently put in commercial operation for coupling an a-c three-phase 50-cycle system with a single-phase $16^2/_3$-cycle trolley system, converting as much as 3,000 kw. A similar electronic converter has been placed in operation, of a capacity of 1,600 kw, coupling a 50-cycle three-phase system with another three-phase system which has a frequency of 42 cycles. Both installations have already given several thousand hours of satisfactory service.[9,10,24]

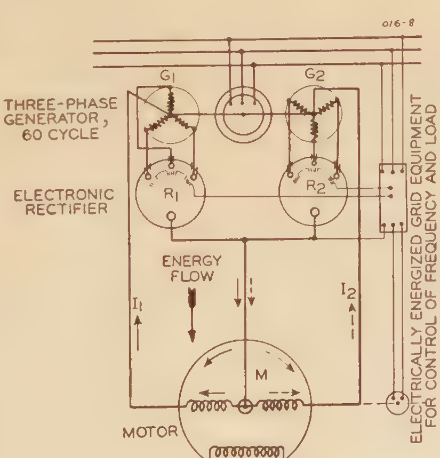


Figure 8. Simplified circuit diagram for demonstrating flexibility of electronic frequency converter

Let us therefore describe this system more fully by means of a simplified circuit, figure 8. This circuit may have no practical value, but will permit ready analysis of all the phenomena with which we shall be concerned.

The scheme represented in figure 8 comprises two a-c synchronous generators, G_1 and G_2, feeding a two-winding d-c motor (M) through a connection without appreciable resistance and through rectifier tubes R_1, R_2, each tube being equipped with control grids. Neglecting the voltage drop in the connections and in the rectifier, the generator, let us say, induces a voltage E somewhat higher than the back electromotive force of the motor. Energy will then flow from the generator to the motor if the grids are energized so that the anodes of the rectifiers are permitted to carry current. Let us assume that one electric valve, R_2, is blocked and therefore current will flow only through the left-hand winding of the motor, bringing it up to speed in the direction indicated by the heavy arrow. The motor will operate in this direction as long as current I_1 produced by generator G_1 can flow through R_1. At a certain instant of time the grids of rectifier valve R_1 are negatively energized by the auxiliary grid equipment, current I_1 is prevented from flowing, and the motor comes to a stop, see figure 8. However, at the same time the grids of R_2 are de-energized and since generator G_2 impresses a potential E_2, current I_2 will flow through the right-hand winding of motor M and bring this motor up to speed; however, in the opposite direction. It can therefore be seen that by impressing a negative potential on grids of rectifier R_1 and then on grids of rectifier R_2, this motor will reverse at a frequency equal to the frequency of the voltage applied to the grids of these two rectifier valves. The frequency of the reversal of motor M is independent of the frequency of generators G_1 and G_2—in other words, independent of the frequency of the voltage applied to the anodes of rectifiers R_1 and R_2. Further, it can be seen that the frequency of reversal of motor M is independent of the frequencies of generators G_1 and G_2 whether these generator frequencies are the same or not.

Let us now apply the above reasoning by following the circuit of figure 9, and we shall find that with a simple control device for energizing the grids, power of a 60-cycle frequency can be converted into

single-phase energy of 25-cycle frequency if the grids of the anodes of the left-hand unit and those of the right-hand unit are energized consecutively with potentials of opposite polarity. The reversal frequency of the grid potentials would have to be equal to the frequency of the single-phase output, namely, 25 cycles. In this arrangement, however, instead of a reversal of direction of rotation, a reversal of voltage on the primary of the single-phase transformer takes place, which is at the rate of 25 cycles if the grids are controlled from the single-phase 25-cycle network.

A more specific arrangement of the grid control is shown on the left-hand side of figure 9. The potential of the grids is controlled by three mechanical contacting devices m, m_1, and m_2, and is supplied by a battery. The devices m_1 and m_2 which are driven in synchronism with the frequency of the three-phase system therefore energize the grids at the same frequency as the anodes of each group, S_1 and S_2, of the rectifier-inverter. However, contactor m supplies the battery potential to each of the contactors m_1 and m_2, or, in turn, to each group of anodes S_1 and S_2, according to the speed of motor M_2. This motor, as can be seen, is driven from the 25-cycle system and, if of the synchronous type, will energize the grids of each group negatively through the battery and contactor segment m once during each revolution or, if a two-pole motor is used, at the frequency of 25 cycles. If the frequency of the single-phase system changes, then the speed of rotation of contactor m changes, and accordingly the interval during which the brush is in contact with the segment. The groups S_1 and S_2 may therefore furnish current for shorter or longer intervals which will be reflected in the frequency of the energy transferred to the single-phase system. Therefore, the frequency of the energy transferred to the primary winding of the single-phase transformer from the three-phase network follows the frequency of the impulses of the contactor m, and since this device is driven by a synchronous motor M_2, energized by the single-phase system, it follows the frequency changes of this system. A completely flexible coupling of the two systems is therefore effected.

The same results can be obtained by using electronic instead of mechanical control equipment, see figure 10. Comparing this with the mechanical control shown in figure 9, the circuit of the electronic control can easily be analyzed. A 12-anode rectifier with electrically controlled grids is connected to the secondary windings of a 60-cycle transformer. The energy-storing equipment comprises a reactor and a battery of capacitors. The control devices consist of grid-controlled tubes and 60- and 25-cycle auxiliary transformers.

Relative Advantages and Disadvantages of Different Methods of Frequency Changing

The discussion below will deal especially with the system shown in figure 10, or similar ones, and only touch lightly on other methods of frequency changing.

From the foregoing it could be seen that the system as shown in figure 2 with an intermediate d-c step does not make it possible for the three-phase network to take care of the reactive power of the single-phase trolley system. Synchronous or static condensers would have to be connected to the trolley system, see figure 2, or then the reactive power would have to be furnished by rotating converters connected in parallel with the electronic converters. Furthermore, in order to obtain successful operation, a reactor has to be connected into the d-c link for reasons given in the second section of this paper. This method, however, permits transferring energy in either direction and may show some additional advantages after more experience has been obtained with d-c transmission of power. Furthermore, this method provides a completely flexible link between the two systems, has a high conversion efficiency (since a high intermediate direct voltage can be chosen making the arc losses negligible), and possesses effective regulation and protective features by means of energized grids.

Such systems for conversion of three-phase power into direct current and back into another three-phase system have been operating in the United States and Europe for many years. These systems make use of intermediate direct voltages of 3,000, 15,000, and up to 48,000 volts, respectively.[11,21,23,27] Although these systems are three-phase to three-phase conversions, still they deserve careful study when considering new frequency-changing equipment for railroad electrification.

Figure 9. Circuit diagram of electronic frequency converter showing mechanical grid-control equipment

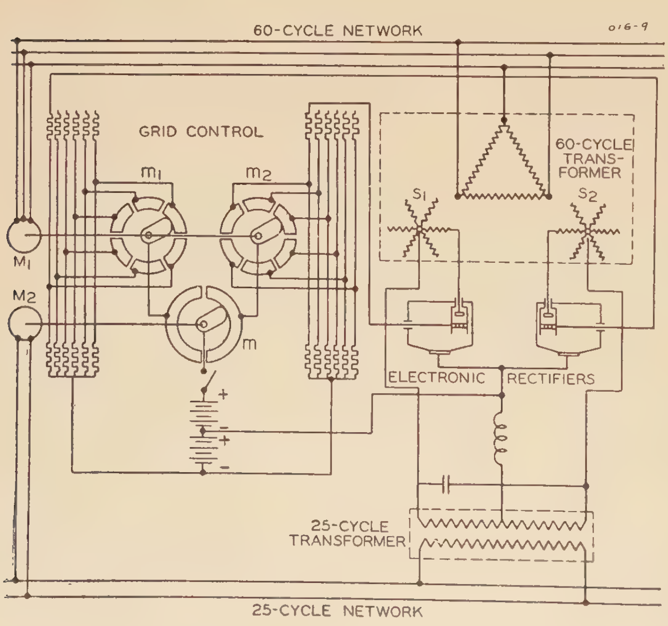
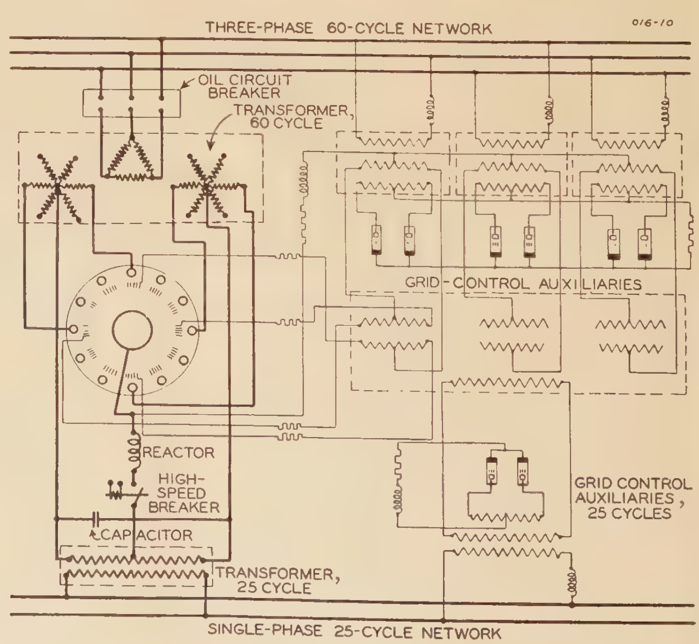


Figure 10. Circuit diagram of electronic frequency converter showing static electronic grid-control equipment



The direct-coupled system (no intermediate step), although it can be made flexible, did not receive much attention in the initial tests nor was such equipment installed on some of the European railway systems. The output voltage for the rectifiers is determined by the trolley voltage and will therefore be fairly high for all existing electrified $16^2/_3$- or 25-cycle lines, and the anodes of this rectifier as well as of the inverter are subjected to a high commutation voltage.

The indirect-coupled systems permit the selection of the most suitable rectifier-inverter voltage in order to utilize the anodes to the fullest degree as the single-phase transformer ratio can be chosen accordingly. Both methods, shown in figures 7 and 10, have been utilized and are therefore given further consideration below. The investigations were made based on a set for 5,000 kw, a power factor of 70 per cent, and conversion of power from 60 to 25 cycles at conventional alternating voltages. The rating of 5,000 kw for the electronic converter sets was chosen in order to be in line with the rating of the present single-phase feeder transformers as used on one of the main electrified lines. Both sets are static and permit the same ease of starting, and may therefore be applied in the same way in connection with electrified lines.

The rectifier-inverter tanks consist of several anodes equipped with energized grids and their necessary control devices. The first method of this kind, see figure 7, necessitates an abnormal number of anodes per tank and an exceedingly accurate control device. Furthermore, the transformer connections are quite abnormal and require a relatively complicated design. The other indirect-coupled system makes use of normal rectifier-inverter tanks with grids, a 60-cycle three-phase transformer with double six-phase secondary, and interphase transformers, both being of the same types as used in standard rectifier installations, and a 25-cycle transformer, single-phase with mid tap.

It can therefore be realized that this last-mentioned system deserves careful consideration. However, some of the main characteristics of both these indirect-coupled systems will be discussed below. Since most of these systems are flexible they have to be compared with motor generator sets which permit elastic coupling of two networks.

Voltage Regulation

From figure 11*a* it can be seen that the voltage regulation is similar to the regulation of a standard transformer. Curve 3 shows the regulation of a transformer, and

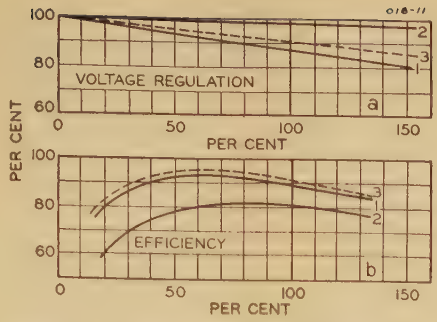


Figure 11. Performance characteristics of a typical electronic frequency converter of 5,000-kw rating compared with a transformer and flexible rotating converter of equal rating

curve 1 that of a 5,000-kw frequency changer, while curve 2 gives the voltage regulation of a motor generator set. It may be pointed out, however, that should this voltage drop, of about seven per cent at full load, be objectionable, a curve similar to number 2 could be obtained by means of additional grid-control devices, as shown in figure 10. This voltage regulation is naturally due to the drop in both of the transformers, in the reactors, and the arc drop of the rectifier-inverter. As pointed out above, the voltage of the intermediate system can be chosen independently of the voltage of the a-c systems, and therefore if chosen at 2,500 volts, for instance, the regulation due to the rectifier-inverter arc drop would only amount to about one per cent at 5,000-kw load.

It may be pointed out that the voltage regulation of such a frequency changer is not affected by fluctuations of frequency nor by the phase relation between the voltages of the two networks, as is the case, for instance, in a synchronous motor generator set.

Efficiency

Not only is the efficiency of such a set higher at full load compared to a motor generator set, but it becomes relatively higher at lower loads. From figure 11*b* the efficiency of such a unit, curve 1, can be compared with the efficiency of a motor generator set, curve 2, as well as with that of a transformer, curve 3. The arc drop of the rectifier-inverter is very low and therefore the efficiency of such a frequency changer is also practically the same as that of a transformer, which can couple two networks of different voltages, but naturally cannot couple two networks of different frequencies.

It may be mentioned here that efficiency measurements on some of the actual installations to which reference was made previously reached as high as 93 per cent at full load. Curve 2 refers to a motor generator set of a design which permits flexible coupling of the two systems.

Due to the fact that in the installations referred to above the load factor is relatively low, about 25 per cent, the average difference in efficiencies between the motor generator set and the rectifier-inverter amounts to about 15 per cent. In other words, the losses are reduced very appreciably by this new type of converter. This, as pointed out above, is mostly due to the fact that the efficiency of such a type of frequency changer maintains a very high value, even at low loads.

Power Factor

A certain amount of wattless power has to be supplied by an external source to a frequency changer of the electronic type. This is required for the magnetization of the transformers and partly also on account of the phase displacement existing between the voltage and the current in this type of equipment, especially if grid voltage control is employed. In case of a system as shown in figure 7, if the energy-storing equipment is omitted, the power factor would probably only amount to about 60 per cent. In other words, a very high component of wattless energy would have to be furnished from the a-c supply system. However, with an arrangement such as shown in figure 10, a power factor of as high as 95 per cent can be obtained. Analysis shows that economically it will be feasible to equip such a set with an energy-storing equipment. However, it may be pointed out that in case the capacitors should fail for any reason, the frequency changer would not be affected in its operation. However, it would then adversely affect the three-phase system, by drawing additional wattless power, and causing an unbalance of the three-phase system.

Protective Equipment

In all considerations referred to above, reference was made repeatedly to grid-control equipment in connection with regulating the valve action of the rectifier and inverter, as well as regulating the voltage. It may be pointed out, however, that the grids may be used for another purpose also, namely, to protect the equipment in case of abnormal operating conditions and disturbances on the line as well as short circuits and backfires.[28] Extensive tests in many installations have proved that the electrically energized grids are able to interrupt the current flow in a tank such as proposed for the above frequency-changer set. The equipment required for this purpose consists of relatively inexpensive devices which permit

energizing the grids of the inverter with a negative potential in case of sudden disturbances. Recent tests have shown that this time can be confined to less than one-sixth of a cycle. Naturally this equipment will not eliminate breakers completely but may make it possible to use switching devices of lower rating.

Feeder and Trolley Voltages

It can easily be realized that since any ratio between primary and secondary voltage on both transformers can be chosen, no additional equipment will be necessary in case the single-phase 25-cycle system would require a higher voltage than commonly used. In the case of a motor generator set, it would probably not be advisable to generate directly a voltage of 25,000 volts or higher, but instead a transformer could advantageously be connected between the single-phase generator and the trolley system.

Space Requirements

Present installations have shown that a considerable saving in space can be obtained with this type of frequency changer. Furthermore, the cost of foundations and building can be greatly reduced, similarly as in any mercury-arc-rectifier installation.

Flexibility of a Static Frequency-Changer Set

As pointed out repeatedly, a set as shown in figure 10 can operate without losing its stability even in case of severe frequency variations on either of the two systems, or during heavy load swings.

Telephone Interference

As mentioned in the introduction, the installation of one of these frequency changers caused relatively serious disturbances in the adjacent telephone lines. However, it must be realized that this installation was fed from a relatively small power source, and therefore the wave-shape distortions due to the rectifiers were transferred to the a-c networks without appreciable diminution. For large railway systems, where many units would be used, it may be possible to take care of this situation by establishing such phase relations between the different units that a multiple-phase system could be obtained, as was done in one of the largest rectifier plants recently installed in this country.[22]

Conclusion

It can thus be seen that there are several methods which permit coupling of networks of different frequencies with static electronic devices. The first system, using an intermediate d-c step, has a considerable drawback in that no wattless power can be transmitted from one system to another. However, it has proved very successful for coupling three-phase networks.

The direct-coupled system, although it does not have the above-mentioned disadvantage, necessitates that the output voltage of the rectifier-inverter be equal to the single-phase voltage and requires that single-anode rectifiers be used.

The indirect-coupled system, on the other hand, permits choosing any output voltage for the rectifier-inverter, allows the exchange of wattless power from one system to another, and permits full flexible coupling. The methods used in Europe, necessitate a 3:1 ratio between frequencies, and cannot be applied to the electrified railway systems in the United States where frequency conversion from 60 to 25 cycles, or a 2.4:1 ratio is necessary. However, the conversion of frequencies, as is necessary in this country, may subject the anodes of the rectifier-inverter to a more favorable load cycle than in case of the frequency ratios required in Europe.

In order to give a proper comparison between the characteristics of these converters of the electronic type with those of the rotating converters at present used, a rating of 5,000 kw was selected for ready reference.

It could be seen from the foregoing that the main advantages of an electronic frequency changer are high efficiency, very simple operation, no necessity for special starting equipment or high starting load, instantaneous starting up of the equipment, small weight of the equipment, especially of the control equipment, which reduces costs for housing and foundation.

The disadvantage of such converters, in so far as can be seen at present, is the distortion caused by them on the three-phase supply network, unless somewhat large and costly energy-storing devices are employed.

It may also be pointed out that the present installations referred to should make it possible to develop in the future frequency changers of this type for very large capacities which may also become a very useful means for the conversion of power for present electrified systems now using 60-to-25-cycle motor-generator converters.

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24. The Flexible Coupling of Systems, by Means of Mutators, Restores His Independence to the Station Operator, While Increasing the Economical Operation of the Systems,

Circuit Interruption by Air Blast

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Synopsis: By using the prestored energy of compressed air for the twofold function of circuit interruption and circuit-breaker operation, a new and original oilless circuit interrupter has been evolved. This air-blast circuit breaker has a guillotine-like arc-interrupting characteristic and can be made practically immune to the adverse effects of circuit recovery voltage.

The historical background of oilless circuit breakers is discussed with particular reference to European designs. The electrical and mechanical design of air-blast circuit breakers for indoor use and the factors affecting that design, are described in some detail.

IN VIEW of the desire to eliminate oil in electrical apparatus evidenced by the electrical power industry, research activities conducted during the past decade have been directed toward the development of a satisfactory current-interrupting principle, not involving the use of oil, but capable of application over the same ranges of current, voltage, and interrupting-capacity steps as the oil circuit breaker.

Fundamental Requirements

It has been recognized that to be acceptable to American power engineers, it is essential that any oilless circuit breaker must be compact, simple in operation, reliable, economical, and easily adaptable to the various forms of circuit connection and mounting at present obtaining for the oil circuit breaker. In addition, the desirability of obtaining an increase in interrupting efficiency has been recognized.

Development of Air-Blast Breaker

It is economically advisable and expedient that American manufacturers should avail themselves wherever possible of the operating experience and evolutionary test data appertaining to successful European designs, for, by so doing, much development time and expense can be eliminated, resulting in ultimate savings to the user. This procedure has been followed in the case of the air-blast breaker here described, thereby resulting in an initial American design from which outstanding reliability of operation has been obtained. A typical indoor air-blast circuit breaker of American manufacture is shown in figure 1.

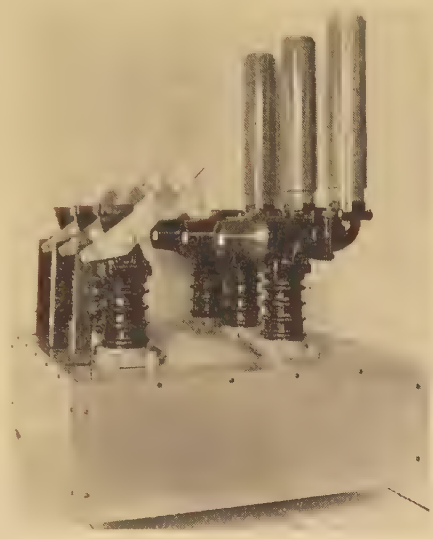

Figure 1. Type AB indoor air-blast circuit breaker, 1,200 amperes, 15,000 volts, 500,000-kva interrupting capacity having active operating parts enclosed

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European air-blast circuit breakers, of both axial and cross-blast designs, have been found to be subject to certain limitations so far as their ability to interrupt high currents is concerned. In addition, these limitations are aggravated when high rates of recovery voltage obtain.

In view of the mechanical advantages and operating experience of a certain European design, it was thought desirable to so improve the design of the interrupting chamber as to increase the maximum interrupting current ability of the breaker to the point where it would be adequate for use on American power systems. To this end, considerable laboratory research was conducted.

In the typical European type of axial air-blast breaker interrupting chamber, the compressed air approaches an orifice through a converging port, and exhausts through a diverging throat. In many European designs, too, the interrupting contact is a part of the isolating contact. This arrangement makes for inefficiency of the interrupting air blast as will be shown later in the paper.

As the result of extensive research, it was found that the arrangement of interrupting chamber shown in figure 2 has a greater interrupting efficiency, particularly at high currents, than the European type of converging-diverging chamber.

It will be noted from figure 2 that the American development incorporates a structure having parallel walls. Redesign of the cooling chamber to obtain increased air velocity, and the introduction of concentric metallic cylinders within the arcing chamber, produced further improvement. Main current-carrying contacts, as distinct from the arcing contacts, were also added.

Operating Characteristics

The design here described capitalizes on the mechanical operating experience and reliability of the European design and, using the prestored energy of compressed air for both circuit-breaker operation and circuit interruption, produces a practically constant circuit-interrupting characteristic, with the result that arcing times of one-half cycle or less are consistently produced throughout the interrupting range of any particular breaker, as shown in figure 3. The typical interrupting test oscillogram, shown in figure 4, shows the short arcing time obtained with this design.

As a consequence of the short arcing time, contact burning is very low and many repetitive operations can be made without contact renewal.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

It has also been found that the interrupting action can be so controlled as to be independent of system characteristics, since it is possible to control the rate of rise of recovery voltage across the interrupting contacts immediately following arc interruption by means of the automatic insertion of resistors which prevent the occurrence of high-frequency transients and reduce the instantaneous values of generator electromotive force appearing at the moment of arc interruption.

Axial-Blast Application

Tests have proved that when using an axial-blast form of interrupting chamber, there is an optimum distance of break between the arcing contacts which produces a maximum interrupting effect. Figure 5 shows the relationship between megavolt-amperes interrupted and arcing-contact separation, with air pressure and port area constant. Obviously, it is desirable that in any air-blast circuit-breaker design, the arcing contact separation should be that which provides maximum interrupting efficiency.

Separation of Interrupting and Isolating Functions

It is evident that, since in indoor air-blast circuit breakers the maximum interrupting efficiency is achieved with a short arcing-contact separation of only one-half inch, considerations of circuit isolation require a co-operating disconnecting means.

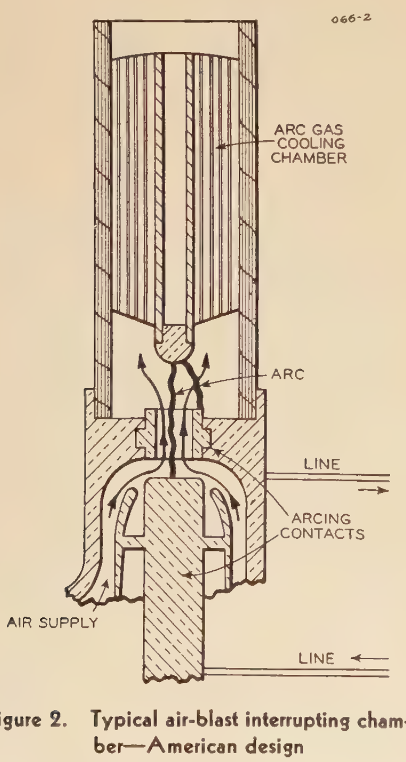
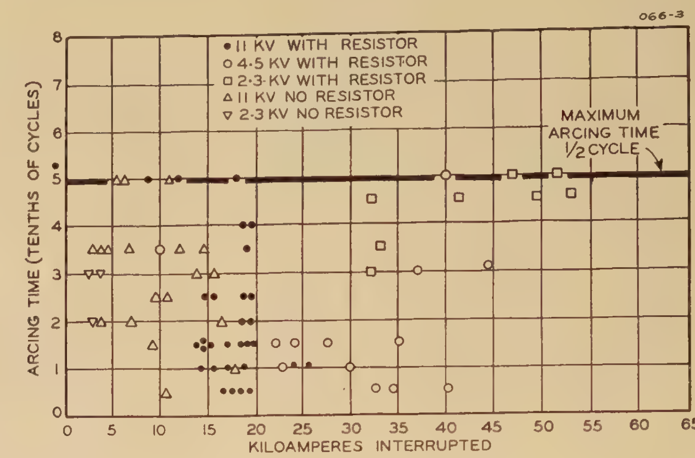


Figure 2. Typical air-blast interrupting chamber—American design

This necessitates an initial arcing contact break sufficient for the maximum interrupting efficiency, immediately followed by an appropriate isolation break, in series, opening under no-load conditions.

Figure 3. Graphical representation of interrupting-test data showing arcing time in tenths of cycles



The use of an independent interrupting contact also permits a very speedy opening of the arcing contacts during interruption, since the inertia of these contacts is relatively negligible when compared with the energy available in the compressed air. The isolating means takes the form of a disconnect switch, and is operated by the same pneumatic energy that opens the interrupting contacts and interrupts the circuit.

Compressed air used for operation of the contacts constitutes a pneumatic co-ordinating device which acts as a positively functioning mechanical interlock of unlimited flexibility. The relative diameter and volume of the operating devices, and of the air ducts leading to them, provide a superior timing means with which to insure proper sequential operation.

Closing Capabilities

Completion of the circuit through the breaker during closing, is achieved by means of the closing of the disconnecting or isolating contacts only, since, except during the interrupting process, the arcing contacts are held closed by the action of heavy springs.

Actual contact, during closing, is made between the movable disconnecting or isolating blade contact and a laminated wedge-type stationary contact. Burning, during closing, is very slight. Even when closing against currents of 140,000 rms amperes and above, there were only slight evidences of scorching or pitting.

The reason for the low contact-burning characteristics of the air-blast breaker during closing is in the very high speed of closing obtained. In order to burn a given quantity of contact material a definite amount of energy is required. Since time is a factor in the energy equation, and since, due to the high closing speed, the period of arcing during closing is extremely short, the breaker can be closed against very high currents without appreciable damaging effects, and with practically no heating or pitting of the contacts. It is especially to be noted that no blast of air on the contacts is required during the closing operation.

Separation of the interrupting and closing functions between two sets of contacts divides the contact deterioration consequent upon these functions; thereby lengthening the over-all contact life of the breaker.

Trip-Free Interrupting Contacts

As in the air-blast breaker the interrupting contact is free to move independently of, but co-operatively with the isolating or disconnecting means, it is essentially trip free in its position and relation to the disconnecting contacts. This fact is of great advantage, especially in the higher-voltage outdoor breakers where extremely rapid interrupting and reclosing times are required.

Breaker Arrangement

A typical design of indoor air-blast breaker is illustrated in figures 6 and 7. A compressed air tank (1), fitted with a main air blast valve (2), forms the foundation on which the active parts of the breaker are mounted. The arcing chambers (3) and disconnect movable members (5) are supported by hollow insulator columns attached to the tank assembly. The arcing chambers exhaust into cylindrical mufflers. Operation of the disconnects is achieved through insulated link (6) and shaft (7), connected to air pistons (8) and (9). Valves (10) and (11) control the air supply.

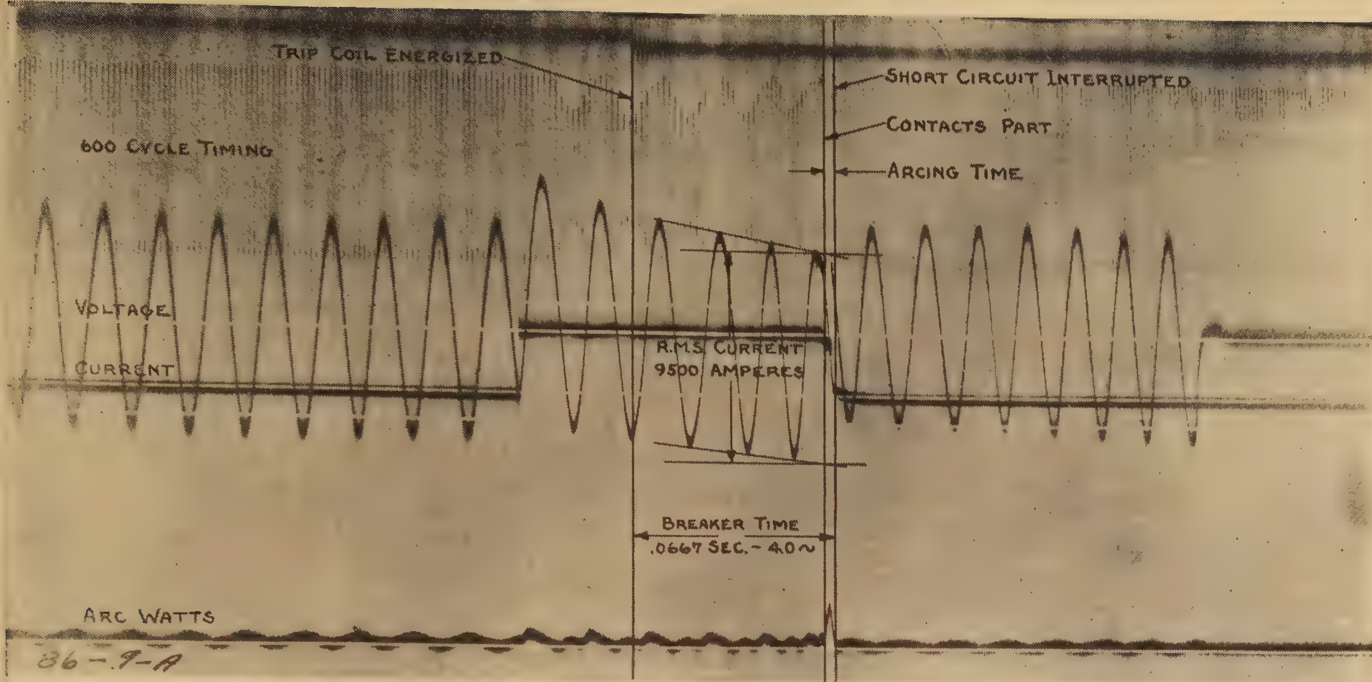


Figure 4. Type AB air-blast-circuit-breaker interrupting-test oscillogram

CO operation at 192,000 kva at 11 kv interrupted by a breaker having a 250,000-kva interrupting rating

Operation

Opening

When opening, electrical or manual actuation of control valve (11) results in opening of the air-blast valve (2), admitting air at 135 pounds or 215 pounds per square inch gauge pressure into the interrupting chambers.

Movable arcing contact (14), normally held closed by the action of heavy springs, is attached to a piston. As air pressure builds up within the interrupting chamber, the piston is depressed, withdrawing contact (14) the required distance away from the stationary arcing contact and air-blast orifice (13), drawing an arc between the contacts. As the tubular stationary contact is the only outlet for the compressed air, a blast of high-velocity air is simultaneously impelled across the initial arcing zone, resulting in limitation of arc-energy release and preventing reignition after the first current zero.

Simultaneously with the admission of air to the interrupting chamber, air pressure is applied to piston (9) resulting in opening of the disconnect contacts (5), under no load, as soon as arc interruption is complete.

Immediately the disconnecting contacts open, an auxiliary contact interrupts the circuit to valve (11), closing the valve. This cuts off the air supply to valve (2) and permits the air remaining on the reverse side of this valve to escape. The main valve then closes under the influence of a heavy spring and the pressure of air remaining in the tank; pressure in the arcing chamber falls and results in reclosing of the arcing contact due to spring pressure.

The air required for arc interruption causes pressure in the breaker air tank to fall. Since the tank is permanently connected to a compressed air storage system, the supply of air within the tank is quickly replenished.

Closing

When closing, electrical or manual actuation of control valve (10) causes compressed air to be admitted to the closing cylinder (8), resulting in the closing of the disconnecting switches. As the arcing contacts are already held closed, the closing of the disconnecting switches completes the circuit.

A simple mechanical interlock insures that all switching operations, once initiated, will be carried to completion. A mechanical trip-free device permits immediate reopening of the disconnecting switches in the event of their being closed against short circuits, even though air pressure may still be exerted upon closing piston (8).

Reliability of Operation

The successful air-blast breaker has to be more than an interrupting device. It must have adequate insulation, and must be able to carry its rated current continuously without exceeding prescribed temperature limitations. Also, like all circuit breakers, it must be capable of operating many times a day without failure of mechanical parts, and yet, on the other hand, be capable of operating satisfactorily after having stood for a period of time without being operated. Several years of experience in the manufacture and operation of

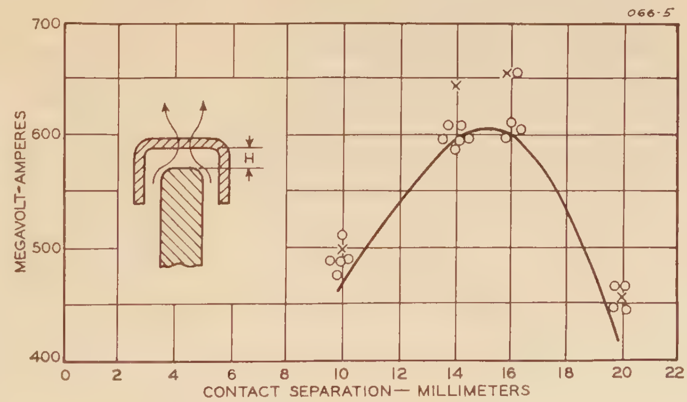


Figure 5. Relation between interrupting-contact separation and interrupting ability in megavolt-amperes

Circles—Effective interruption
Crosses—Interruption with remnant arc
(Air pressure and port area constant)

air-blast circuit breakers have provided knowledge of the proper materials to use in mechanical parts, such as pistons, valves, valve seats, piping, and interlocks; giving assurance that the breaker can accomplish repetitive operations, as well as function satisfactorily, when infrequently operated.

Apart from the two solenoid control valves for closing and tripping the breakers, there is only one valve which must seal against the air pressure. This is the main air-blast valve, which is a simple composition valve, easily accessible. The method of mounting this main air-blast valve is such that the air pressure in the storage tank acts on the valve to secure tightness.

General Factors Affecting Design

The most efficient circuit breaker is the one in which, all other things being equal,

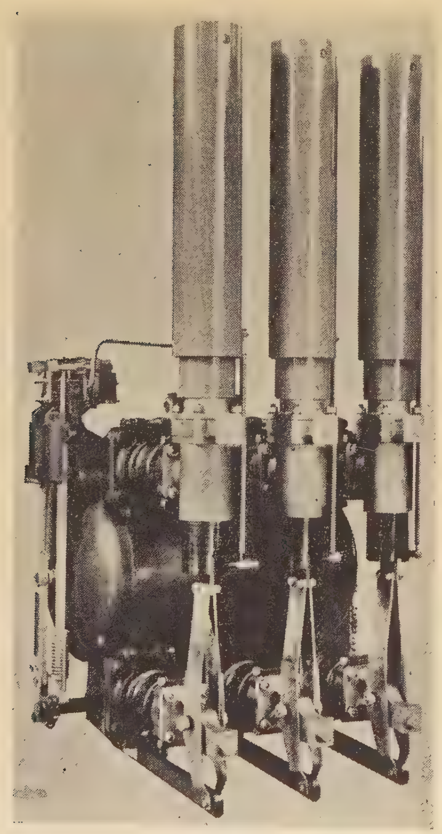


Figure 6. Type AB air-blast circuit breaker with vertical mounting arrangement, 600 amperes, 15,000 volts, 500,000-kva interrupting capacity—equipped with arc-paralleling resistors

the rate of dielectric recovery between the arcing contacts, immediately following the first passage of the current wave through zero, after parting of the contacts, is always greater than the rate of recovery voltage rise across the contacts. Under these circumstances, restriking of the arc is impossible and the maximum period of arcing is one-half cycle.

In designing a circuit breaker, there are two lines of attack by which maximum interrupting efficiency may be obtained. First, by the production of a high rate of dielectric recovery and second, by limiting the rate of rise of the recovery voltage. These two factors are used in the design of air-blast circuit breakers with such marked success as consistently to produce arcing times of one-half cycle or less.

Tests have proved that there are four factors which influence the interrupting capacity of high-voltage air-blast circuit breakers. These are:

1. Air pressure
2. Port area
3. Series breaks
4. Automatic insertion of resistors

The first three of these factors contribute toward control of dielectric recovery. The fourth factor produces a measure of control over the rate of rise of recovery voltage. The proper correlation of such of these factors as may be required produces air-blast circuit breakers of almost any desired interrupting capacity in the sizes usually required. This holds true for a wide range of interrupting capacities and for all standard voltage ratings up to and including 220,000 volts.

Factors Affecting Dielectric Recovery

Air Pressure

Dielectric recovery between the arcing contacts of air blast breakers is assisted by three different air-pressure characteristics. These characteristics result in the following:

1. Dynamic effect
2. Dielectric effect
3. Cooling effect

Dynamic Effect. Initial opening of the arcing contacts is effected by means of the air pressure itself. An arc is drawn between the contacts, but is immediately enveloped and centralized by the dynamic action of the air under high pressure.

An arc may be visualized as an incandescent core of concentrated electrons surrounded by an incandescent envelope of ionized gas. Due to the dynamic effect of the compressed air, the arc is centralized and its length controlled. This contributes toward limitation of arc energy release.

During the process of arc extinction the air pressure rapidly forces the arc products and any ionized gas into an arc gas cooling chamber, and so produces extremely rapid scavenging and deionization of the arc path.

Dielectric Effect. That the dielectric value of air increases due to compression, is well known. When under a pressure of about 135 pounds per square inch, the dielectric value of air is approximately equivalent to that of high-grade oil. Due to the passage of this high-dielectric medium between the contacts an inherently rapid build-up of dielectric is obtained.

Cooling Effect. The compressed air usually employed, is under a pressure of either 135 pounds or 200 pounds gauge per square inch. It is obvious that the sudden release of such pressures in the arc zone, and the instantaneous expansion of the air, will create intense cooling action.

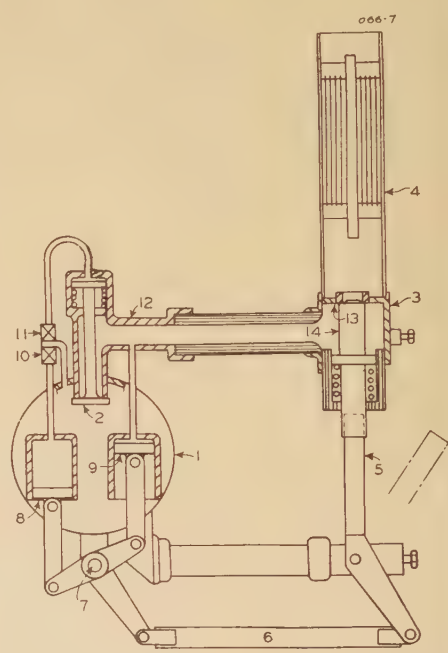


Figure 7. Typical type AB air-blast-circuit-breaker pole section

The cooling action deionizes the arc and limits its conducting ability by reducing its cross section.

Due to the inherent characteristics of an a-c system, the cross section of the arc diminishes as the current approaches zero. This causes an increase in the relative cooling effect of the air blast immediately before current zero.

Total Effect of Air Pressure. The combination of a high-velocity high-dielectric cooling medium produces the maximum interrupting effect and is responsible for the short interrupting time of one-half cycle or less, experienced with most air-blast breakers.

Due to the short arcing time, and the low release of arc energy, contact burning is greatly reduced. Consequently, long contact life is obtained, even when interrupting high currents. Many thousands of interruptions are obtainable without the necessity of contact renewal.

Many interrupting tests with varying short-circuit currents, and at different air pressures, have proved that a definite relation exists between interrupting capacity and air pressure. As shown in figure 8, the increase in interrupting capacity is almost proportional to the increase in pressure.

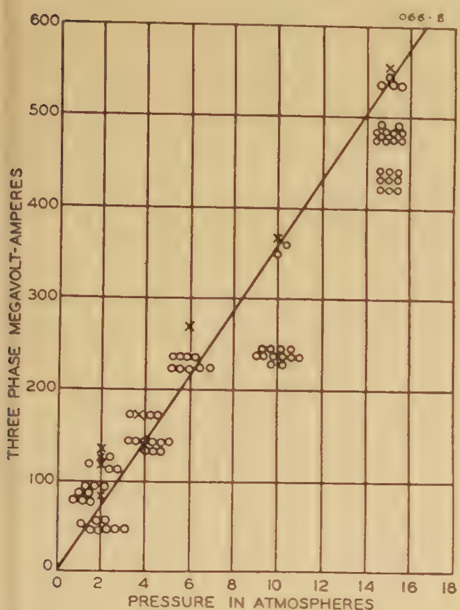


Figure 8. Relation between air pressure and interrupting ability in megavolt-amperes

Circles—Effective operations
Crosses—Ineffective operations
(Port area constant)

Port Area

Since a definite control is obtained by means of the dynamic, dielectric, and cooling effects of the air blast, it follows that these effects will be increased if the volume of air made available is increased, provided that the air pressure remains constant.

By increasing the area of the port, increased interrupting capacity is obtained as shown in figure 9. The proportional relationship between the area of the port and the interrupting capacity there shown has been verified by a large number of tests.

Series Breaks

As the recovery of dielectric between the arcing contacts depends more or less directly on the pressure of the air, it follows that, provided air pressure remains constant, an increased measure of dielectric recovery should be obtainable by connecting a number of breaks in series.

Tests have proved that while an improvement in interrupting capacity can be obtained by the use of series breaks, the increase in capacity is not in direct proportion to the increase in the number of breaks as is shown in figure 10.

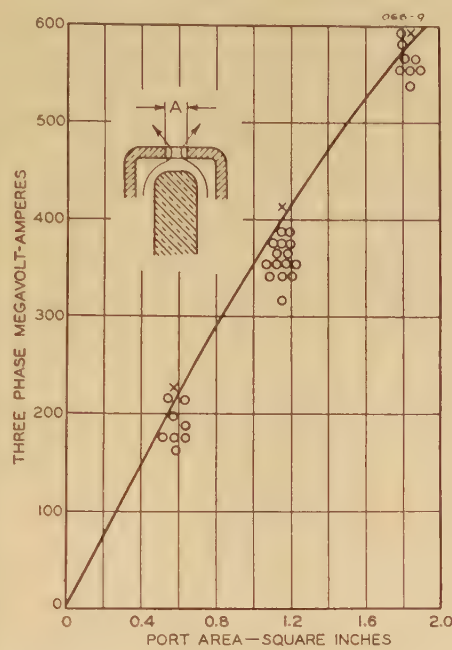


Figure 9. Relation between port area (orifice) and interrupting ability in megavolt-amperes

Circles—Effective operations
Crosses—Ineffective operations
(Air pressure constant)

There are practical limitations to the use of series breaks. Mechanical design factors, insulation difficulties, and costs increase with each additional break. It is also obvious that the expenditure of air must increase with each additional break.

The electrostatic relations which cause unequal voltage distribution across series breaks, increase with the number of breaks. In the case of the indoor air-blast breakers here described, one break per phase is sufficient in all cases.

Factors Affecting Rate of Rise of Recovery Voltage

Insertion of Resistors

On circuits where the impedance consists largely of reactance, the power factor at the moment of arc interruption may be low. Due to the lower power factor, current zero occurs at a time when the generator electromotive force would normally be in the vicinity of its crest value, so that, at the moment of interruption, the voltage across the contacts rises rapidly to a value corresponding to the generator electromotive force.

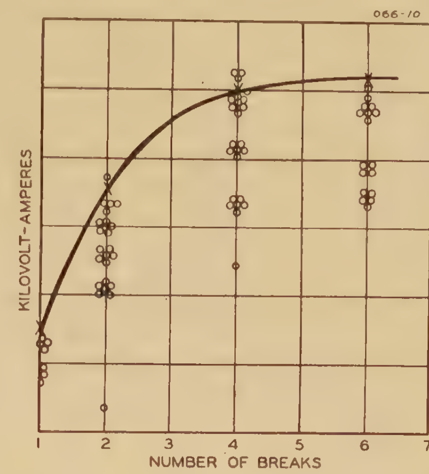


Figure 10. Relation between number of breaks in series and kilovolt-amperes interrupted

Circles—Effective operations
Crosses—Ineffective operations
(Air pressure and port area constant)

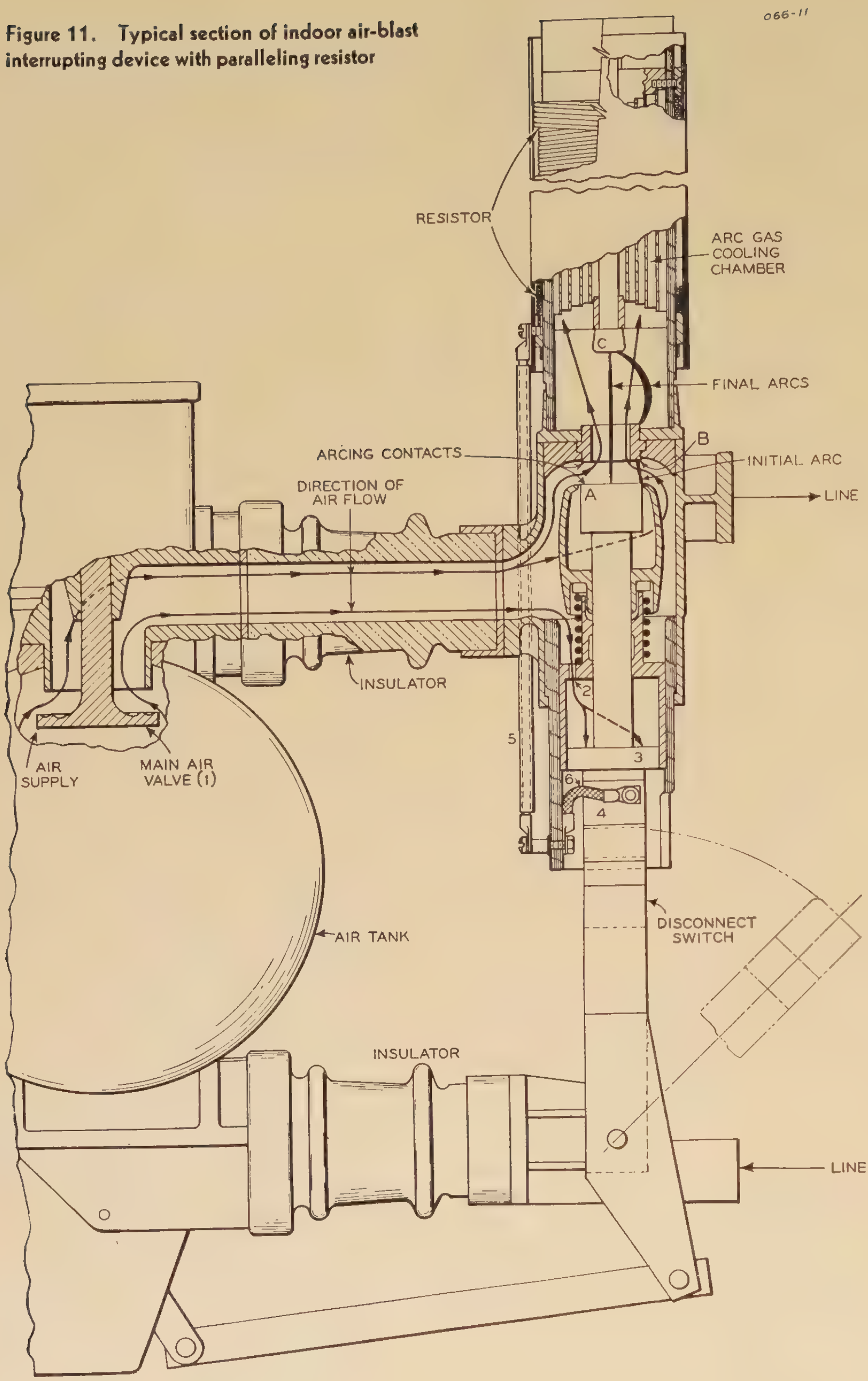
The rate at which the voltage rises is affected by the characteristics of the circuit under interruption, and also is dependent upon the instantaneous value of the generator electromotive force at current zero.

Upon interruption of the short circuit, the stored energy in the system tends to discharge, since a-c circuits are composed of both inductance and capacitance. The well-known inductive kick from coils of many turns, such as field coils, illustrates one type of circuit discharge. The snapping discharge of a capacitor illustrates another. An interruption on a large power system may produce both of these kicks in magnified form, and in an infinite variety of phase relations.

When the generator electromotive force re-establishes itself, immediately upon interruption of the short circuit, the inductive and capacitive discharge effects are superimposed upon the characteristic form of the normal-frequency electromotive force in the form of a high-frequency transient which may rise to a value as much as twice or more the instantaneous value of the generator electromotive force. This transient is usually a combination of various frequencies which depend upon the natural frequency of different circuit combinations obtainable in the system interrupted.

The rate of rise of the combined recov-

Figure 11. Typical section of indoor air-blast interrupting device with paralleling resistor



ery voltage depends upon the instantaneous value of the generator electromotive force, the amplitude of the superimposed transient, and upon the frequency of the transient.

It has long been known that the rate of rise of recovery voltage can be beneficially influenced by inserting a resistor into the interrupting circuit. In the air-blast breaker limitation of the rate of recovery voltage rise is accomplished by the use of resistors inserted into the circuit by means of the action of the arc itself.

Indoor air-blast circuit breakers having 150,000-kva interrupting rating and higher are usually equipped with paralleling resistors. The method of connecting and mounting the resistor is shown in figure 11. It will be seen that the resistor is noninductively wound around the muffler housing.

As the arcing contacts *A* and *B* separate, an arc is drawn between them and the centralizing action of the air-blast forces the arc into contact with the probing electrode *C*, thereby automatically inserting the resistor in parallel with a portion of the arc during the first half cycle of arc.

As the fault current decreases after reaching its maximum value during the first half cycle, the resistance of the arc increases rapidly, so that the current tends to follow the alternative path from (4) through the resistor in series with the section of the arc from the electrode *C* to the stationary arcing contact *B*. The section of the arc between the moving contact and the electrode then becomes unstable and goes out.

The section of the arc between the electrode *C* and the stationary contact *B* is momentarily maintained after the main arc from the moving contact *A* to the electrode *C* is extinguished, but the fault current is greatly limited due to the high value of the resistance connected in series with the arc.

When the low-current arc between the electrode and the stationary contact is extinguished at or near current zero, improvement in power factor has taken place due to the insertion of the resistance, resulting in a marked reduction in the instantaneous value of the generator electromotive force at the moment of interruption.

The reduction in the rate of rise of recovery voltage obtained by the use of automatically inserted resistors is illustrated in figure 12, which shows cathode-ray oscillographic records of the voltage appearing across the contacts of an air-blast breaker during and after interruption. The upper oscillogram shows the voltage condition when no resistor was used and the lower oscillogram shows the improvement obtained by the use of resistors.

It is apparent that the rate of rise and the maximum value of recovery voltage is much less when an automatically inserted resistor is used. High-frequency transients are practically eliminated and the voltage immediately following arc interruption, follows generally the normal sinusoidal wave form. A representative oscillogram of an interrupting test made on an air-blast breaker equipped with resistors is shown in figure 13.

Summary

It is evident from the foregoing description that the air-blast breaker has several very desirable characteristics.

1. It is an oilless breaker.
2. It can be applied over practically the same range of interrupting-capacity steps and voltages as the oil circuit breaker, both indoor and outdoor.
3. The prestored energy of compressed air is used, not only for circuit interruption but also for opening and closing contacts, and for proper sequential timing.

4. Its current-interrupting range is such as to meet the maximum interrupting-current requirements on each interrupting step.

5. It gives control over the magnitude and rate of recovery voltage rise.

6. Short arcing time permits fast interrupting time.

7. Separation of interrupting and isolating contacts enables fast reclosing.

Conclusion

The air-blast breaker is a scientific product which is a direct result of the availability of high-power circuit-breaker testing laboratories. Its performance under all kinds of conditions, has been checked and rechecked; its operating characteristics and limitations have been determined; and operating security has been assured by the application of adequate safety factors and interlocks.

As a result of the extensive research conducted during the evolutionary process, it is possible to predetermine the performance of this air blast circuit breaker by means of a judicious combination of air pressure, port area, series breaks, and arc paralleling resistors. And so there emerges from the testing laboratory, a unique oilless circuit breaker of simple, sturdy and compact design, which is applicable to practically all current, voltage, and interrupting ratings. Comprehensive and reliable test data enable its adaption to almost any particular set of system characteristics within its rating, and prove its ability to render satisfactory service under the most arduous demands of American power systems.

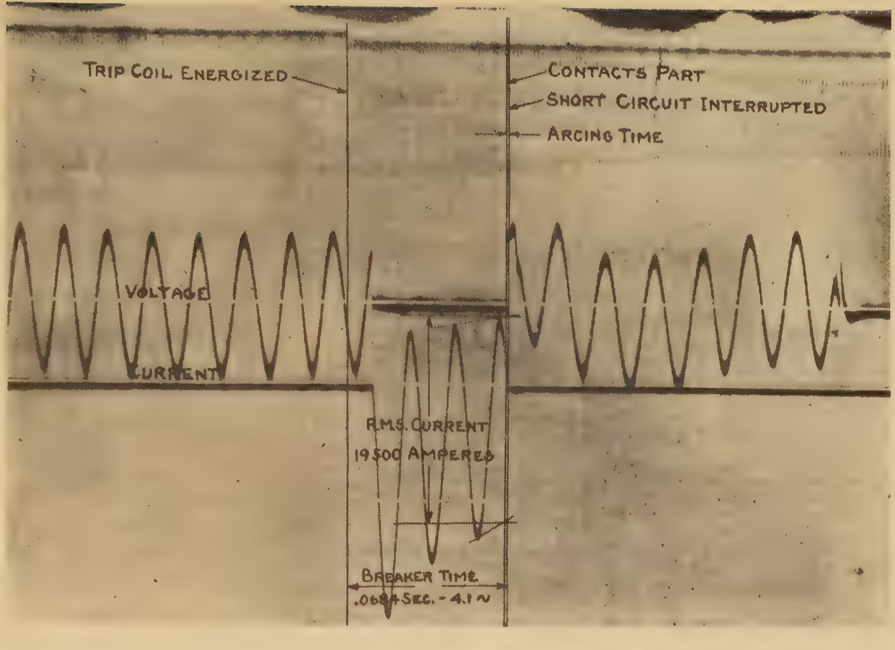


Figure 13. Oscillographic record of interrupting test of a 1,200-ampere 15-kv 500,000-kva interrupting capacity air-blast circuit breaker, when interrupting 429,000 kva at 11 kv. Arcing time 1/600 (0.00167) second

Acknowledgment

During the successful development of the air-blast circuit breaker, reliance has been placed on the co-operative efforts of many individuals. Acknowledgment is here made of valuable contributions from the staffs of the circuit-breaker testing laboratories and engineering departments of the Allis-Chalmers Manufacturing Company and of the Brown Boveri Company.

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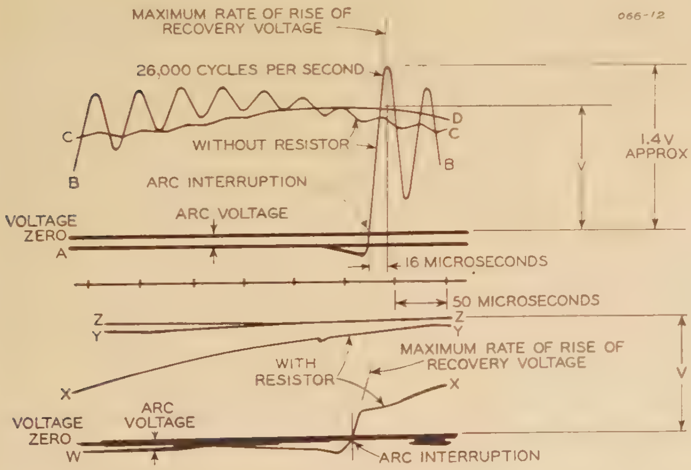

Figure 12. Cathode-ray oscillogram showing prevention, by resistor, of high-frequency transients

Upper section, without resistor, shows transient with frequency of 26,000 cycles. Record starts at *A*, continues to *B*, reappears at *B* (left), continues to *C*, reappears at *C* (left), terminates at *D*. Arc voltage decreased to zero from peak value at interruption point. High-frequency transient appeared; voltage reaching 1.4 times normal maximum sinusoidal value in the short time of 15 microseconds. Oscillations gradually decrease to *D*

Lower section, with resistor, record starts at *W*. Resistor limited voltage peak before arc interruption. Rate of recovery voltage rise greatly reduced after interruption. Voltage-wave rise rate tapered off, following approximately sinusoidal form through *X* and *Y* to *Z*. Maximum voltage value not reached until 750 microseconds

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

The Cross-Air-Blast Circuit Breaker

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Synopsis: The designs of European air-blast circuit breakers are not wholly satisfactory for operation in the United States as they do not handle high enough currents, cannot economically be built for high enough interrupting capacities, and do not conform to United States installation arrangements.

Accordingly, a new type of air cross-blast circuit breaker has been developed which does conform to the above requirements. The commercial design of this circuit breaker is discussed in a companion paper "Design and Construction of High-Capacity Air-Blast Circuit Breakers" by Messrs. H. E. Strang and A. C. Boisseau, and the present paper analyzes the theory of performance of the foreign and cross-blast circuit breakers, and presents evidence from a number of sources which throw light on the method of operation. The circuit breaker is found to operate predominately on the displacement theory. The nature of its performance makes it much less sensitive to recovery rate and high currents and much more economical in air consumption than air-blast breakers previously available.

FOR a number of years air-blast circuit breakers have been built in Europe. These designs have been watched closely; individual breakers have been imported and tested. An air-blast circuit breaker of purely domestic design is now being put upon the market. This circuit breaker is described in a companion paper by Messrs. H. E. Strang and A. C. Boisseau (*Transactions pages 522–7*).

Inasmuch as this design differs completely from foreign practice, it is interesting to examine the reasons for this pronounced difference, and the inner workings of the new device. Figure 1 shows diagrammatically the typical Continental design, which may, for the sake of identification, be described as radial blast. It consists of a male contact and a segmental female contact through which air is discharged when the circuit breaker is opened. The air stream envelopes the male contact on its way to the nozzle. It thus tends to cool the arc and blow the arc products away from the male contact and out through the nozzle. Due to the fact that the arc is extinguished by an independent source of power, the air blast, the performance of such a circuit breaker is highly reproducible and it is an excellent design for analytical study.

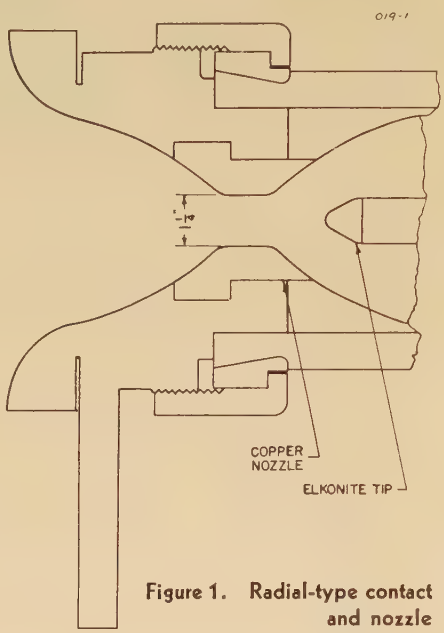

Figure 1. Radial-type contact and nozzle

A considerable number of tests has been made on nozzles corresponding approximately to the Continental designs. Figures 2*a*, *b*, and *c* give the results of such tests. In figure 2*a*, it is shown that with voltage recovery rate and air pressure constant, the current-interrupting capacity is proportional to nozzle diameter. In figure 2*b* it is shown that with voltage recovery rate and nozzle diameter constant, the current interrupted is proportional to air pressure. In figure 2*c*, it is shown that with pressure and nozzle diameter constant, current-interrupting capacity is inversely proportional to recovery voltage rate between limits. This inverse proportionality fails at high currents, therefore, there is a maximum current which can be cleared no matter how low the rate of rise of recovery voltage may be. The design of figure 2*c* corresponds to a Continental rating of 400,000 kva at 10 kv or 23,000 amperes. Examination of the figure shows that at this rating the recovery rate must be quite low, 150 volts per microsecond at 120 pounds per square inch and about 500 volts per microsecond at the breaker's rated pressure, as compared with a figure of 1,800 for the usual testing station. It further appears that the kilovolt-ampere rating must be sharply reduced if the operating voltage is below 8,000 volts no matter how low the recovery voltage may be.

Since United States circuit-breaker standards call for interrupting current ratings as high as 60,000 amperes for a 250,000-kva circuit breaker, it is apparent that the Continental design would have to have a much smaller rating if it were to be applied in any standard manner in this country. Since the nozzle diameter increases as the first power of the current to be interrupted, while the air requirement goes up as the square of the nozzle diameter, the larger nozzle required to meet United States conditions would have a very greatly increased air consumption and would not be an economical design. A satisfactory design for the United States should be able to handle considerably higher recovery rates and at the same time should be able to handle maximum currents with a minimum of air consumption.

Accordingly the cross-blast design described in the Strang-Boisseau paper has been evolved. Figure 3 is a cross section of the interrupting unit. This consists of a pair of contacts located in an arc chute of insulating material. Air is introduced at one side of this chute. The air velocity is, therefore, at right angles to the arc stream and blows the arc against a number of barriers also of insulating material. In effect the arc is caught in the grip of a multiple shear having a movable member consisting of jets of air and stationary members of insulating material. At current zero the arc is cut up into sections and the arc products blown away (through the arc chute) into a muffling structure. This structure lends itself well to observation. All of the usual magnetic and cathode-ray measurements can be recorded and the chute can be made of transparent material so that the behavior of the arc can be observed by high speed photography. The usual high speed cameras operating up to 2,000–3,000 frames per second do not provide enough observations close to current zero. However, a special camera was developed which is capable of a maximum speed of 120,000 frames per second.[13] Since the arc phenomena in the cross-blast chute last for periods between a half and one cycle, the camera was slowed down so as to take 60,000 frames per second, that is, its total of

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D. C. PRINCE, manager of the commercial engineering department, General Electric Company, Schenectady, N. Y., was chief engineer of the switchgear department of the company at Philadelphia, Pa., at the time the paper was presented; J. A. HENLEY is with Metropolitan Vickers Company, Ltd., Manchester, England, and W. K. RANKIN is with the General Electric Company, Philadelphia, Pa.

13. For all numbered references, see list at end of paper.

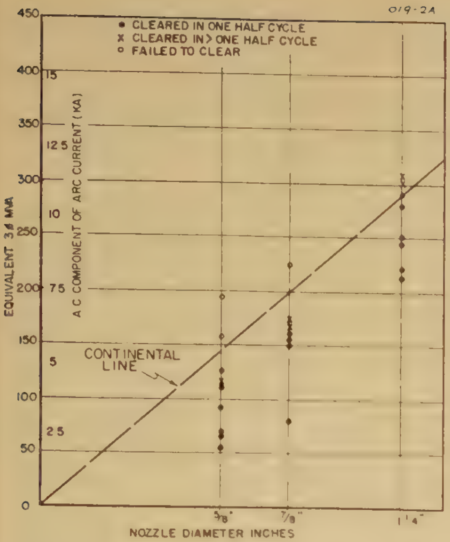


Figure 2a. Variation of rupturing capacity with nozzle diameter at 120 pounds per square inch; radial-type nozzle

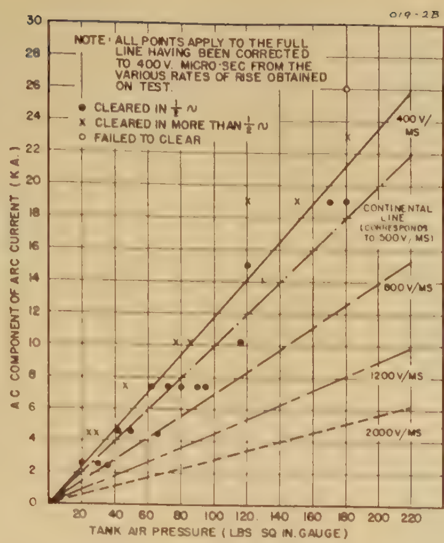


Figure 2b. Variation of rupturing capacity with air pressure; radial-type nozzle

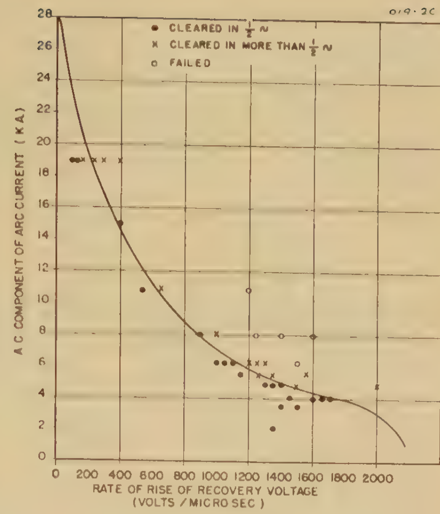


Figure 2c. Variation of rupturing capacity with rate of rise of recovery voltage at 120 pounds per square inch; radial-type nozzle

1,000 frames is distributed over one cycle. With this device, exposures occur at the rate of one every $16^2/_3$ microseconds, or one every 0 degree 20 minutes of arc.

Figure 4 shows some typical enlargements of arcs taken with this camera.

Although much valuable work has been done in which the voltage recovery characteristics of circuits have been assessed on the basis of the recovery rate, or the steepest tangent passing through the origin, it has nevertheless been appreciated from the earliest days of the conception that precise work along this line involved a comparison of the entire voltage recovery curve of the circuit with the curve representing recovery of insulation strength of the interrupting device. For certain other interrupting devices, notably expulsion protector tubes, curves of insulation strength recovery have been determined and published. In the present instance, therefore, an attempt was made to secure as complete a curve as possible between the recovery strength of the circuit breaker and time. In order to secure this curve the circuit breaker was subjected to varying recovery voltage rates high enough to cause the arc to restrike. A cathode-ray oscillogram of such a test shows the voltage first rising across the contacts and then collapsing at the point where a restrike occurs. The value of voltage at which collapse occurs and the associated time provides a point in the time curve of recovery of insulation strength. See appendix *C*.

The solid line of figure 5 is a plot of a recovery characteristic with a number of experimental points shown. Over a considerable range it appears that a straight line through the origin fits the observed points as closely as any other line. It therefore, appears that the conception of recovery rate, that is, a proportionate increase in strength against time, is a useful parameter for this type of circuit breaker. As the recovery voltage rises corresponding to an increasing dielectric strength in the path previously occupied by the arc, however, the point is reached where a breakdown can take place between the contacts over a new path. There is, therefore, a saturation condition. The curve bends over at some value representing the breakdown of the gap. This saturation characteristic appears as a matter of experiment in the solid-line curve of figure 5.

In figure 5, most of the experimental points correspond to a pressure of 3 pounds gauge or 18 pounds absolute. The dashed curve is calculated from the experimental solid curve for 20 pounds gauge or 35 pounds absolute. Two test points are given corresponding to this pressure. The highest points of these two curves are at 40 and 91 kv respectively, or a ratio of approximately 2.3. From the curve in figure 6, the rod-gap dielectric strengths corresponding to the two pressures and adjusted to the proper temperatures are 61 kv and 103 kv, whose ratio is 1.7. From the random nature of breakdown phenomena this is probably as close an agreement as one can expect from so few tests.

Below ten microseconds no experimental points on the solid curve appear. Some discussion will be offered as to the probable shape of the portion of the curve below ten microseconds. However, consideration will first be given to the straight portion of the curve between t_2 and t_3. This part of the curve appears to be consistent with the displacement theory of operation, that is, it is assumed that at current zero an unimpaired wedge of dielectric is driven across the arc path. This wedge increases in thickness at the rate of fluid flow and the product of that rate and the dielectric strength of the wedge gives a measure of recovery strength across the gap:

$$v/t = d/t \times v/d$$

where

v = voltage
d = distance
t = time
v/t = rate of rise of recovery voltage
v/d = dielectric strength
d/t = dielectric velocity

This equation has been evolved for the case of liquid dielectric such as oil, which is relatively incompressible and constant as to dielectric strength. With air which

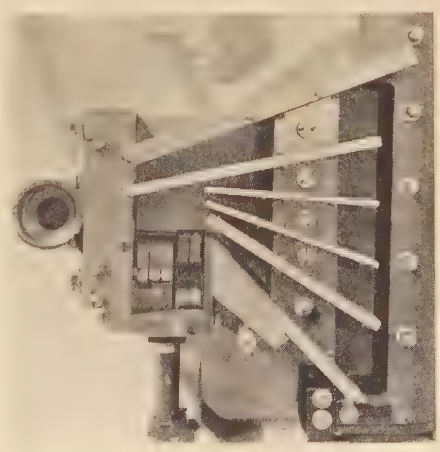


Figure 3. Cross section of interrupting unit of cross-blast air circuit breaker

Figure 4. Photographs of the arc in a cross-blast circuit breaker taken with high-speed camera at 60,000 frames per second

Frames 1 to 25 inclusive are photographs of the arc which is decreasing as it approaches current zero in frame 23. Frame 30 shows the first breakdown, at *B*, from the moving contact to a timing gap at *A*. The breakdown of this timing gap is recorded on the cathode-ray oscillogram and makes it possible to locate the current-zero photograph. In frame 32 these auxiliary arcs appear with greater intensity. Frame 22 shows the $3^3/_8$-inch depth of the cooling plates

obeys the gas laws and has a dielectric strength which is variable with pressure, the matter of determining the proper dielectric strength and velocity to use is somewhat more complicated than with oil. The curve of figure 6 has already been offered showing the variation of dielectric strength with pressure. The

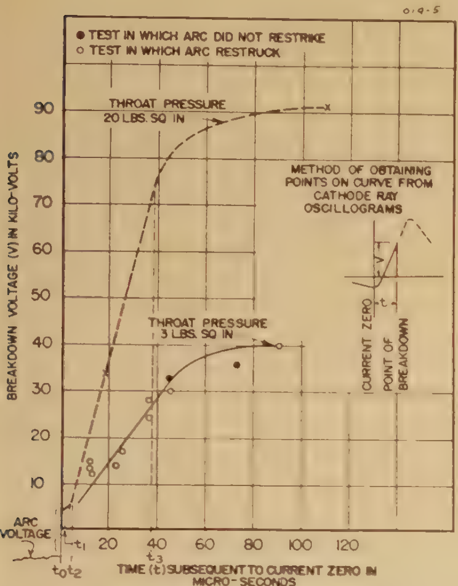


Figure 5. Variation of recovery strength of cross-blast breaker with time

amount of air discharge through an orifice is expressed by the equation:

$$M = Ap\sqrt{\frac{\gamma g}{RT}}$$

where

M = mass discharge in unit time
A = effective orifice area
P = absolute pressure in orifice
T = absolute temperature in orifice
R = universal gas constant
$\gamma = \frac{cp}{cv}$
g = acceleration of gravity

This equation holds provided the receiver pressure is less than 0.53 times pressure in the tank supplying the orifice. Under these conditions, the discharge will be at the velocity of sound. This condition is met by the 20-pound curve of figure 5. In the air at high velocity, the temperature will have fallen in accordance with the equation

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

to -71 degrees centigrade, P_1 being 135 pounds absolute.

At this pressure and temperature the impulse dielectric strength will be 103,000 volts per inch, assuming that the gap between the ionized columns is approximately equivalent to a rod gap. At a temperature of -71 degrees the velocity of sound is 938 feet per second. The data is taken under such conditions that the contacts are separated far enough to bring in to play one barrier in the arc chute. A wedge of air will be driven in on each side of this barrier so that the rate of rise of dielectric strength should be determined by multiplying the dielectric strength just obtained by the velocity of sound and by 2. The resultant figure of 2,320 volts per microsecond is well within the limits of experimental error as compared with the slope of 2,000 volts per microsecond on the dotted curve.

In the deionization or cooling theory of arc interruption the arc space is cooled and deionized. (Doctor Suits[11] has shown that these two phenomena are substantially the same at high pressure.) This cooling causes an increase in arc voltage. Prior to current zero the arc voltage is measured and it is a reasonable assumption that immediately subsequent to current zero it would require that amount of voltage or a greater amount to sustain an arc. Practically, the required voltage should be greater for two reasons. In the first place, some cooling will have taken place during the voltage reversal no matter how quickly that has occurred. In the second place, the reversal must be accompanied by the formation of a new cathode. This cathode effect, however, is small in a high-voltage design such as that under discussion. The curve of figure 5 would, therefore, be expected to start at zero time t_0 at a height corresponding approximately to the arc drop prior to current zero. During the time that the cooling is taking place this curve will rise until when the cooling has become complete the dielectric strength will increase at the rate of interposition of new dielectric. The transition from the curve to the straight line, the slope of which represents the rate of interposition of the new dielectric, is designated as t_2. It is interesting to see what evidence can be obtained regarding the time t_0 and t_2 and what effect it has upon the performance of the circuit breaker.

In this way the recovery characteristic of this circuit breaker can be divided into two parts. One part between t_0 and t_2 in which a cooling phenomenon takes place and the other period subsequent to t_2 in which the operation is on a displacement basis. During the cooling period, displacement cannot be operative because during that period some conductivity exists, and the current flowing through that conductivity disrupts the fresh dielectric as fast as it enters the arc space. As soon as unimpaired dielectric has been interposed, that fresh dielectric will sustain the entire recovery voltage. That part of the arc path still conducting will in effect be short-circuited by that conductivity. The two phenomena, therefore, would not take place simultaneously, but are present, one prior to time t_2 and the other subsequent to it. During the time t_0 to t_1 there must be some conductivity. If that conductivity is appreciable, it should represent a resistance shunted across the contacts, and should alter the curve of the voltage transient. The voltage transient of the test station is known both through calculation and tests of oil circuit breakers. See appendix *A*.

An examination of the tests on the cross-blast air circuit breaker indicates conductivity only at currents above 6,000 amperes and at rates of rise of recovery voltage above 2,500 volts per microsecond. The largest observed conductivity was quite small, resulting in a reduction of the recovery transient peak of only 15 per cent. Qualitatively, if cooling is playing a part in the operation of the circuit breaker, one would expect to find some relationship between clearing and the arc voltage immediately prior to the last current zero, that is, it should be apparent that the circuit breaker is getting ready to clear by a rise in arc voltage prior to the current zero, at which point the clearing actually takes place.

Table I shows a number of tests made at varying currents and pressures together with the arc voltages immediately prior to the last current zero. There seems to be a purely random relation between the

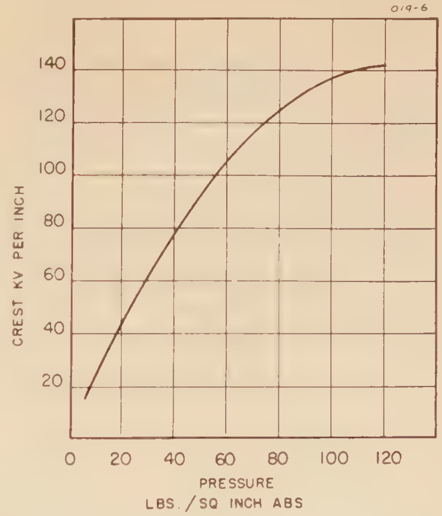


Figure 6. Variation of dielectric strength of air with pressure; impulse breakdown of two-centimeter rod gap in nitrogen at 25 degrees centigrade

arc drop just prior to clearing, so that any effect of cooling on the actual clearing appears to be a secondary phenomenon.

Further qualitative evidence on this subject was obtained by substituting other gases for air. It is known that a small amount of carbon tetrachloride vapor will greatly increase the breakdown strength of air. Accordingly, carbon tetrachloride vapor was added and it was found that the performance corresponded to that which would exist at double the dielectric strength of pure air in accordance with the displacement theory. Since it was conceivable that this increase was due in part to the increased cooling effect from added carbon tetrachloride, a proper proportion of CO_2 was added to give approximately the same increase in the cooling effect but no measurable increase in the performance was detected.

Messrs. I. Kesselring and F. Koppelman[7,8] have proposed an interesting theory on the basis of which the time required to cut the arc path can be calculated for a radial-blast breaker. They assume that the current density in the arc stream is a constant. Under these conditions and with the round arc stream used by them the diameter of the arc is proportional to the square root of the current, a relationship which they claim to have been confirmed by photographs. In the process of cutting off the arc path, the interrupting air proceeds with some velocity. As long as this velocity is greater than the rate at which the arc diameter decreases, the unimpaired air will follow closely the receding boundary of the arc. However, with the diameter changing in accordance with the square root of current, the rate of decrease of the arc diameter approaches infinity as current zero is approached. There will, therefore, be a short time during which the air is not able to keep up with the shrinking arc, and it will not actually cut off the arc space until some time after current zero. If enough data are available this interval during which the arc path is not definitely cut off by displacement is calculable.

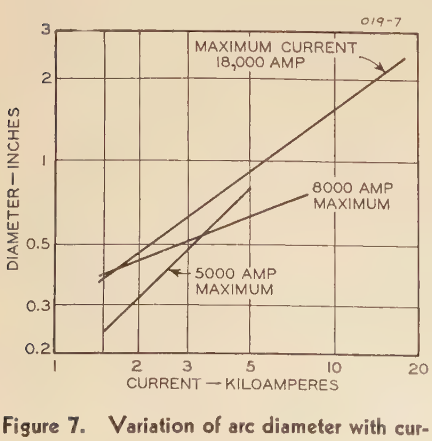


Figure 7. Variation of arc diameter with current, cross-blast circuit breaker

Doctor C. G. Suits has calculated on theoretical grounds that the current density with forced convection is not absolutely constant but that it should vary in such a way that the arc diameter will vary as the 0.77 power of the current, instead of the 0.5 power as assumed by Messrs. Kesselring and Koppelman.

The high-speed photographs provide an experimental measure of the actual diameter of the arc at least as far as it is shown by its effect on the photographic negative.

Figure 7 has been taken from measurements of arcs at three different currents, peaking at 5,000, 8,000, and 18,000 amperes. From these curves the following three formulas can be deduced:

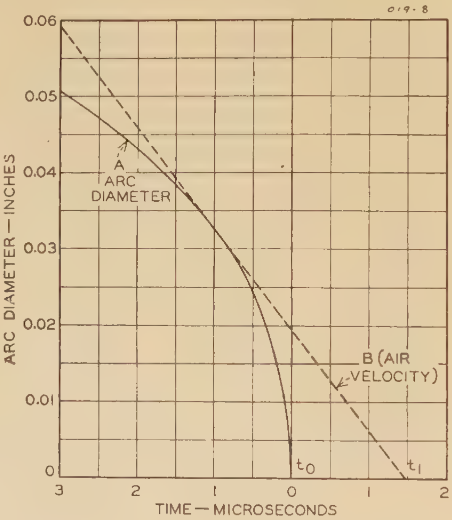


Figure 8. Variation of arc diameter with time, 8,000-ampere arc, cross-blast circuit breaker

With a maximum of 5,000 amperes

$d = 0.000288 i^{1.04}$ inches

With a maximum of 8,000 amperes

$d = 0.021 i^{0.4}$ inches

With a maximum of 18,000 amperes

$d = 0.00163 i^{0.745}$ inches

All of these curves represent measurements during the decay of the arc.

Figure 8 is such a curve of arc diameter against time, drawn to scale with a corresponding curve of air velocity shown tangent to it. If we assume that the separation of the current zero and the arrival of the air indicates the time $t_0 t_1$, then those times for the three currents observed are 0, 1.6, 0.0107 microseconds. From the pronounced variation in exponent derived from figure 7, one is left in doubt whether there is a change in constants with increase in current or whether the three sets of values are due to observational errors. More data should throw light on this point. All three values yield cutoff times so short that it is apparent that one would not expect cooling phenomena to be in evidence except under conditions of a high rate of rise. For instance the least arc voltage from table I is 2,900 volts and the longest time above is two microseconds, giving a rate of rise of 1,450 volts per microsecond.

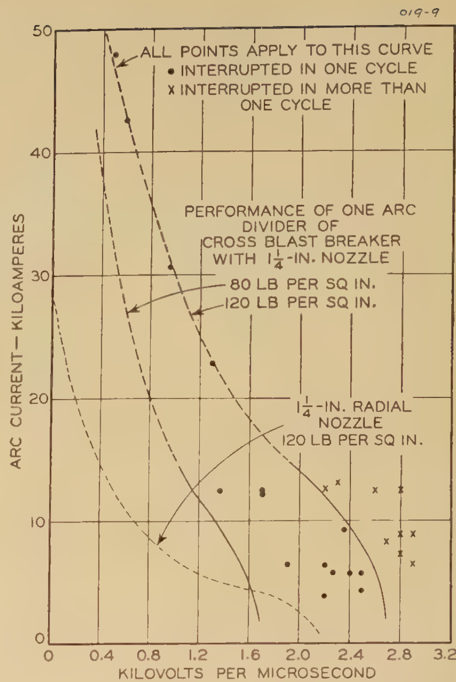


Figure 9. Variation of rupturing capacity with rate of rise of recovery voltage

This gives rise to the question of what needs to be done in the case of an application where the rate of rise of recovery voltage is extremely rapid. There are two alternatives. Either the ability of the breaker may be increased by an increase in air pressure, air volume, or the number of arc barriers introduced into the chute; or arrangements may be made to shunt the contacts with some impedance which will reduce the rate of rise. Both of these expedients can be taken. In order to secure the effect of a resistance shunt, an electrode can be located between some pair of barriers and connected through a resistance to the stationary contact. With such an arrangement the recovery voltage appearing between the contacts after the arc has been interrupted breaks down the gap to this electrode inserting the resistance in shunt with the arc path while any current flowing through the resistance is interrupted by further movement of the contact admitting air to other sections of the arc chute. In the appendix *B* will be found a simple method of calculating what

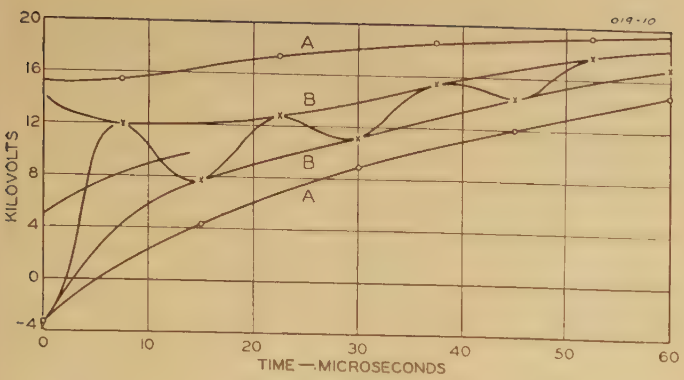


Figure 10. Envelopes of recovery-voltage oscillation, cross-blast circuit breaker

Curve *B* at reduced air pressure

the proportions of such resistors should be. From this point on, it is merely a matter of economics and design whether the recovery rate of any given circuit should be taken care of by a change in the air delivery or by the application of a shunt resistor.

The ability of the cross-blast design to handle recovery rate is much greater than that of a radial blast, particularly at heavy current.

Figure 9 is a curve of current variation with recovery rate corresponding to figure 2*c*. The curve of figure 2*c* has been superimposed and dotted for reference. In the case of the radial blast, all of the air heated by the arc and the arc products must be expelled through the same opening as the air blast. Consequently any current will reduce to some extent the air delivered. In a cross-blast design air is throttled by an orifice before entering the arc chute. As long as the back pressure is less than the critical value 0.53, the amount of air delivered will not change with current over a considerable range. The interrupting ability of the circuit breaker should, therefore, not change as much over a corresponding range and this is shown clearly in figure 9.

Some falling off in the recovery rate ability is noted, but this fall is not nearly as rapid as with the radial nozzle. At high currents gas evolved by decomposition of the chute structure begins to be added to the air discharge in such volume that it adds appreciably to the interrupting capacity of the chute. The dotted portion of the curve in figure 9 represents an extrapolation of the actual test curve beyond the point at which it was possible to secure failure to locate the curve exactly. At high currents enough gas is evolved from the chute structure to interrupt the circuit without any air supply. The extrapolation of this curve, therefore, represents ability known to be present in the interrupting structure but not necessarily the maximum capacity of it. The full-line curves of figure 9 correspond to clearing in one cycle with only one barrier in action. As the contact continues its travel two or more barriers come into action with resultant increase in interrupting ability as shown by the crosses on the figure. These points are not comparable directly with the points for one barrier since no limit in interrupting capacity was reached. It will be noted that at say 1,000 volts per microsecond the cross-blast chute interrupts over four times as much current with the same air consumption or conversely, a radial nozzle to have the same interrupting capacity would be 4.3 times as big in diameter and consume 18 times as much air.

As mentioned at the beginning of this paper, it is hoped that the foregoing will give a clear idea of the reasons why, for low-voltage designs particularly, it has been necessary to develop a new type of interrupting air-blast structure. The behavior of that structure has been analyzed and it has been shown under most conditions to operate on a displacement basis. The small area in which operation is by cooling has also been defined. For heavy currents, the ability of this design, instead of decreasing toward zero volts, actually rises until at the highest currents the circuit is interrupted even without the aid of the air blast.

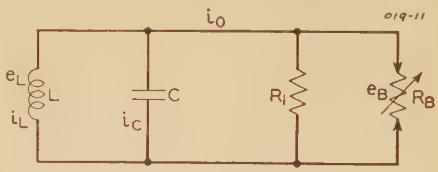


Figure 11. Test circuit

Table I. Interrupting Tests

Test Number	Arc Amperes, RMS	Arc Duration (Half Cycles)	Arc Length (Inches)	Reactor Tap Number	Kilocycles Per Second	Applied Air Pressure (Lbs Per Sq In.)	Peak Arc Voltage (Maximum Kv)	Peak Recovery Voltage (Kv)	Rate of Rise of Recovery Voltage (Volts Per Microsecond)
186	1,950	0.9	0.9	6.6/0	26	40	3.4	29	1,710
187	1,920	0.8	0.8	6.6/0	26	30	3.4	30	1,770
188	1,970	0.9	1.0	6.6/0	26	30	2.5	32	1,900
190	1,950	2.7	3.6	6.6/0	26	23	5.1	32	1,900
188	1,970	3.7	4.9	6.6/0	26	18	6.2	32	1,900
191	1,920	4.2	4.5	6.6/0	26	7	5.4	31	1,830
194	4,100	2.2	3.0	2.7/0	40	28	5.7	25	2,280
192	4,100	3.0	3.8	2.7/0	40	25	5.1	25.5	2,320
193	4,100	2.4	3.5	2.7/0	40	25	4.3	25.2	2,300
203	5,700	1.9	2.3	1.7/0	45	47	4.5	22	2,240
196	5,400	2	2.5	1.7/0	45	45	6.2	20.6	2,100
199	5,400	1.1	1.3	1.7/0	45	40	2.8	20.6	2,100
201	5,900	2.5	3.2	1.7/0	45	27	3.9	21.3	2,170
197	5,600	3.1	4.5	1.7/0	45	23	5.2	20.6	2,100
202	5,900	3.1	3.7	1.7/0	45	13	3.4	21.3	2,170
204	8,500	1.1	1.1	0.93/0	70	45	3.4	15.2	2,420
206	8,300	2.5	2.3	0.93/0	70	40	3.4	13.8	2,200
205	8,300	2.2	2.7	0.93/0	70	25	3.4	12	1,910
210	11,100	1.5	1.8	0.47/0	100	58	2.9	9.6	2,180
209	11,300	1.5	1.6	0.47/0	100	55	3.4	8.3	1,880
211	10,800	1.8	2.1	0.47/0	100	33	2.9	8.2	1,860
213	10,600	4.4	4.7	0.47/0	100	15	2.9	7.7	1,750

Appendix A. Air-Circuit-Breaker Leakage Current*

It has been pointed out that the interruption process can be divided into two periods: one during which a path of finite resistance exists between the electrodes; and a second characterized by infinite resistance but finite dielectric strength. This fact is well illustrated by a series of tests from which the actual magnitude of the leakage resistance and current are determined. It was found that at constant recovery rate, current, and voltage, air pressure could be reduced until a leakage current flowed after the current zero.

Figure 10 shows the envelopes of the recovery-voltage oscillation as taken from cathode-ray-oscillograph records of two tests taken at the same voltage and with the same circuit. Test *B* was made at considerably reduced air pressure.

The complete circuit employed in the tests consisted of a generator and an external reactance in series with the breaker. Both generator and reactance had considerable

* Prepared by Robert M. Bennett.

distributed capacitance to ground, consequently the recovery voltage was composed of two frequencies, one relatively low, and the second, due to the presence of the series reactance, of the order of 60,000 to 100,000 cycles per second.

For the purpose of analysis of the high-frequency oscillation, this circuit can be generalized as indicated in figure 11, in which L represents the inductance and C the equivalent capacitance to ground of the external reactance. R_1 represents the ordinary damping resistance of the circuit and might have been placed in series with the inductance without altering the final conclusions. R_B represents the breaker resistance. The vibration modulus of the high-frequency oscillation is:

$$p=-\frac{1}{2\dfrac{R_1R_B}{R_1+R_B}C}\pm\sqrt{\frac{1}{\left(2\dfrac{R_1R_B}{R_1+R_B}C\right)^2}-\frac{1}{LC}} \qquad (1)$$

Since $2\dfrac{R_1R_B}{R_1+R_B}C \gg LC$ the angular frequency of the oscillation is

$$\omega=\sqrt{\frac{1}{LC}}$$

and C may be determined, the inductance

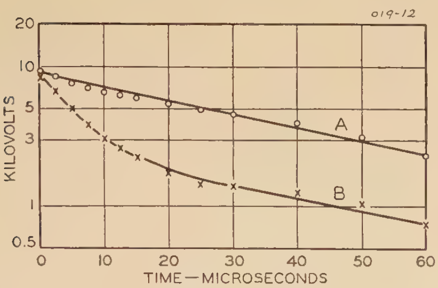


Figure 12. Magnitude of recovery voltage envelopes

Curve B at reduced air pressure

being known. The envelope of the high-frequency oscillation will be of the form

$$y=\epsilon^{-\frac{R_1+R_B}{2R_1R_BC}t}$$

and this envelope plotted on semilog paper has the slope

$$D=-\frac{R_1+R_B}{2R_1R_BC} \qquad (2)$$

Figure 12 shows the magnitude of the envelope of the recovery voltage during two tests, test B being at reduced air pressure.

These curves are direct evidence of the occurrence of displacement during the operation of the breaker. Curve A made at high air pressure shows that at all times after the current zero, the damping of the circuit was due to a constant value of resistance, hence the breaker resistance must have been infinite.

Curve B which indicates a greater rate of damping for 15 microseconds becomes parallel to curve A showing that in this case also displacement occurred although the air pressure and velocity were greatly reduced. The slope of curve A is given by $D=-\dfrac{1}{2R_1C}$ and the value of R_1 is found from the relation

$$R_1=-\frac{1}{2DC} \qquad (3)$$

If R_1 is known it is possible to find R_B from equation 2 above, that is

$$R_B=-\frac{R_1}{1+2R_1DC} \qquad (4)$$

The above method of calculation is useful for determining the breaker resistance after the first peak of the recovery voltage. For values previous to this peak the exact value

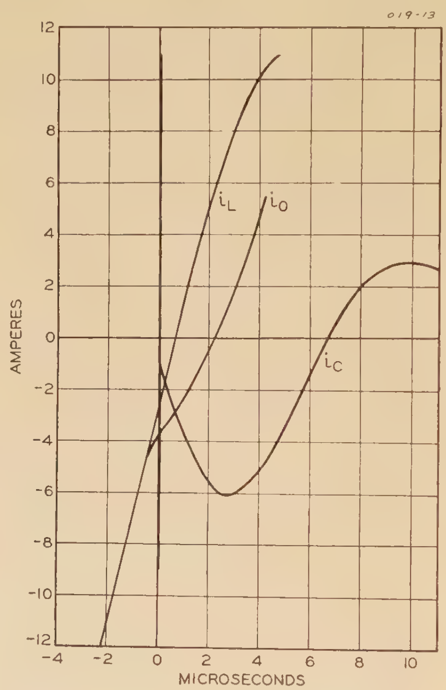


Figure 13. Construction of currents, test B

of the voltage envelope is in doubt and the breaker current can be determined as follows:

Referring to figure 11

$$e_L=-L\frac{di_L}{dt}$$

and the slope of the inductance current is given by[5]

$$\frac{di_L}{dt}=\frac{-e_L}{L}$$

The capacitor current is found from the relation $i_C=-C\dfrac{de}{dt}$ consequently both i_C and i_L can be drawn if any single value of inductance current can be determined. Since it is evident that i_0 must be zero when $e_B=0$, it is possible to determine the inductance current at this instant by $i_L=i_0-i_C=-i_C$.

These currents as plotted for the low-pressure air test are shown in figure 13.

The resistance of the breaker is then found from

$$\frac{R_1R_B}{R_1+R_B}=\frac{e_B}{i_0}$$

or

$$R_B=\frac{1}{\dfrac{i_0}{e}-\dfrac{1}{R}} \qquad (5)$$

It was found that this latter method is useful only until the time of the first recovery voltage peak as the mechanics of constructing the inductance current introduce considerable error.

In figure 14 are shown the complete current, voltage, and resistance characteristics for the air breaker operating with low air pressure.

Points marked with circles are calculated from equation 5 and points marked with crosses from equation 4.

Appendix B†

Calculation of a Resistor for Controlling Voltage Recovery Rates

The ohmic value of resistance to limit the recovery rate to a given value is given by the equation:

$$R=\frac{\dfrac{de}{dt}\times 10^6}{\dfrac{di}{dt}}=\frac{\dfrac{de}{dt}\times 10^6}{2\sqrt{2}\pi fI}=$$

$$\frac{\dfrac{de}{dt}\times 10^3\times V\times\sqrt{3}}{2\sqrt{2}\pi f\times kva}=3.25\frac{de}{dt}\times\frac{V}{kva}\ \text{(for 60 cycles)}$$

where

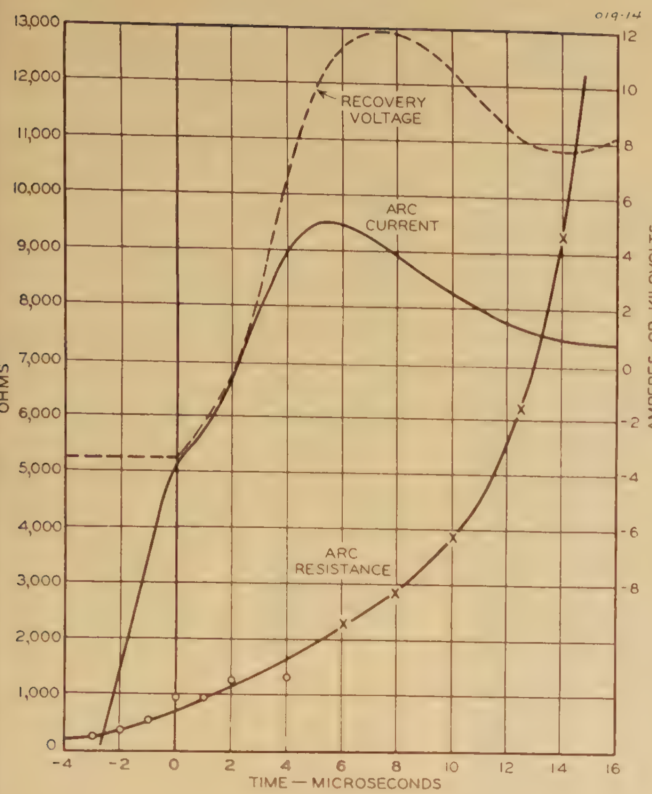
R = the ohmic value of the resistance
$\dfrac{de}{dt}$ = the specified limit of recovery rate in volts per microsecond
$\dfrac{di}{dt}$ = the limit of the rate of change the instantaneous value of short-circuit current just prior to interruption
f = system frequency
I = maximum available interrupting current in rms symmetrical amperes
V = application voltage in line-to-line volts
kva = interrupting duty in kilovolt-amperes, three phase

This value of resistance should be used on each pole.

The amount of active material required may be based on the allowable temperature rise for one operation on the assumption that all of the heat developed remains in the active material. If the breaker is properly designed, the maximum duty will be about one-quarter cycle at $1^1/_2$ times leg voltage. The amount of active material is then given by:

$$M=\frac{Q}{h\Delta T}=\frac{950\times .75\times(\text{kv})^2}{240h\,\Delta T\times R}=2.97\frac{(\text{kv})^2}{h\cdot\Delta T\cdot R}$$

† Prepared by W. F. Skeats.



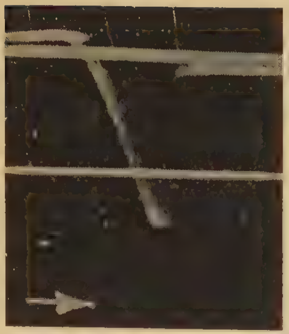


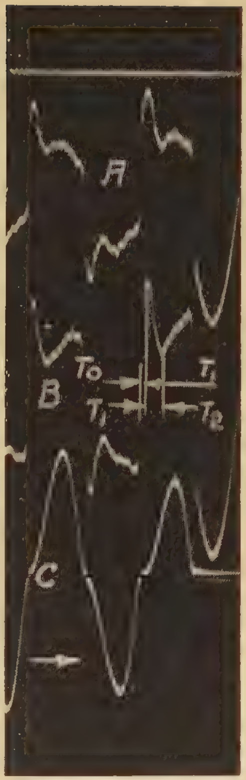
Figure 15. Breakdown in cross-blast air circuit breaker

3.7 microseconds per millimeter

Figure 14 (left). Variation of leakage current and resistance with time

Figure 16 (right). Breakdown of an arc which has been cooled to the point of interruption

A—Line voltage
B—Arc voltage
C—Current



where

M = active material required in pounds for each pole
Q = heat generated in resistance in Btu
h = specific heat of material; Btu per pound per degree Fahrenheit
ΔT = allowable temperature rise for one operation, Fahrenheit
R = resistance in ohms
kv = application voltage in line-to-line volts

Appendix C

The type of breakdown that occurs in the air-blast breaker is of particular interest because it indicates the nature of interruption to be similar to the breakdown of a dielectric. A cathode-ray-oscillograph record of such a breakdown is shown in figure 15.

The recovery voltage rises at a rate which is in accordance with circuit characteristics and then collapses to zero voltage in less than two microseconds.

This failure of the cross-blast air circuit breaker was intentionally caused by reducing air pressure and increasing the rate of rise of recovery voltage. The character of the failure is similar to that of the disruptive breakdown of a rod gap in air.

As there is nothing shown in the oscillograph record which would indicate progressive breakdown, we conclude that it was occasioned by the overstressing of the cold air of the blast which had been inserted between the arc path ends after current zero. In other words, there was an interruption by displacement but breakdown occurred due to the fact that the recovery voltage rose faster than the dielectric strength.

In contrast with this sharp breakdown the slowness of thermal breakdown is illustrated by the magnetic oscillograph record figure 16.

It will be noted that there were attempts to interrupt which were partially successful and finally the arc was extended to a point where successful interruption was obtained. The rate of rise of recovery voltage is less than ten times faster than the 60-cycle voltage wave which is less than 40 volts per microsecond and indicates that its rate of rise was limited by leakage current.

The collapse of voltage T_1 to T_2 required approximately 2,000 microseconds which indicates clearly that it was progressive in character and was caused by a gradual decrease in the resistance of the arc path.

These two cases have been chosen as they are typical of the extremes. Figure 15 is the disruption breakdown following displacement with no deionization phenomena visible. Figure 16 is the progressive breakdown from a reversal of the deionization process with no displacement in operation.

Cases may be found where displacement and deionization by cooling may both play a part in arc interruption; however, in the cross-blast air circuit breaker, displacement will account completely for interruption at low currents and be a predominating factor even for the high currents and recovery rates.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Magnetic "De-ion" Air Breaker for 2,500–5,000 Volts

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Synopsis: The theory of quenching an arc by deionizing the normally conducting arc stream, utilizing a gas blast produced by means of an intense transverse magnetic field, is elaborated. Application of design principles dictated by this theory has made it possible to develop a new form of air circuit breaker for 2,500–5,000-volt service. These breakers are completely described, the theory of the De-ion interrupters is discussed, and test results are submitted. The problem of adequately enclosing the breakers is considered and it is shown that excellent interruption can be obtained in an enclosure of small over-all dimensions.

INTERRUPTION of 2,500- and 5,000-volt circuits capable of producing fault currents equivalent to 150,000 kva, by breakers using air as the interrupting medium, is not readily accomplished without special arc-quenching chambers. In open air impractically long arcs are necessary to clear circuits supplied at these voltages. Comparatively simple air circuit breakers have been built utilizing magnetic blowout means for lengthening the arc in an interrupting chamber of reasonable dimensions, but even with the constricted path available for the arc in such chambers, it is necessary to lengthen the arc to approximately five feet in order to achieve interruption. The energy dissipated in such an arc is necessarily high because of the long arc length and consequent high arc voltage. Interruption in such cases is not achieved primarily by establishing a process of rapid deionization in the vicinity of current zero, but depends rather upon building up the arc voltage to such an extent that restriking after an early, forced, current zero does not take place, even though intensive deionization is not provided during the time of substantially low recovery voltage following the current zero.

It is usually necessary to mount air circuit breakers for 2,500–5,000-volt applications in compact metal-clad switchgear. Consequently, efficient interruption with a minimum of arc energy, size of interrupting chamber, and formation of ionized gases is required. These features call for the development of arc-interrupting means which will open the circuit using a comparatively short arc, relatively low energy input, and effective deionization at the first current zero. In the next sections a circuit breaker is described which has these qualities and which is shown to be adequate for 150,000 kva at 2,500 or 5,000 volts when mounted in enclosures of small dimensions.

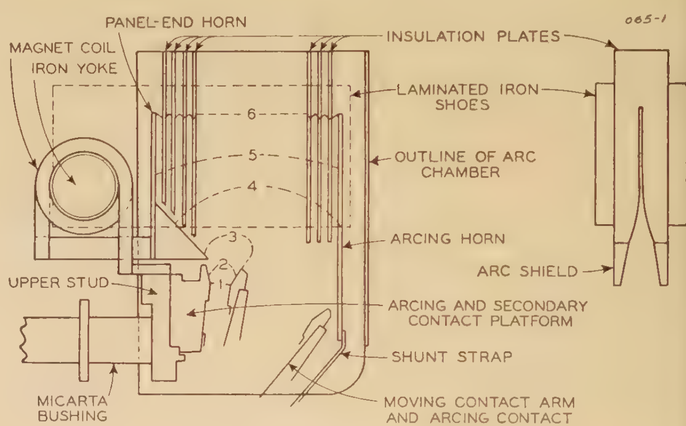

Figure 1. A diagrammatic sketch showing partial sections of the magnetic De-ion interrupter

The dotted lines 1, 2, 3, 4, 5, and 6 indicate progressive positions in arc interruption

De-ion interrupter

To interrupt an a-c circuit with minimum dissipation of energy, a switch is required which does not substantially impede the flow of current until it normally reaches zero, and which quickly takes on insulating properties thereafter. This means appears to be more advantageous than depending upon a high arc voltage and the associated high energy input to effect interruption. Synchronization of interruption with a current zero may be obtained by separating switch contacts and forming an arc which must be controlled to develop dielectric strength, following the current zero, more rapidly than voltage is impressed by the circuit.[1] This deionization action may be accomplished in a number of ways—for example, by the use of a blast of gas produced by decomposing a gas-forming material,[2] or by the use of a plurality of copper plates with short arcs between them to take advantage of the spectacular dielectric recovery at the cathode of an arc.[3] A more recent method which employs a magnetically produced gas blast for deionization was presented by Ludwig and Grissinger in their paper "A New High-Capacity Air Circuit Breaker".[4] An experimental review of the various interrupting means available indicated that this latter method was most suitable for interruption of high currents at 2,500 and 5,000 volts, because of its simplicity, effectiveness, and freedom from undesirable flame and noise.

Application of the magnetic-deionizing principle results in constructing an interrupting chamber as shown diagrammatically in figure 1. The chamber consists of a large number of non gas-forming insulating plates having V-shaped slots which are spaced apart and placed at right angles

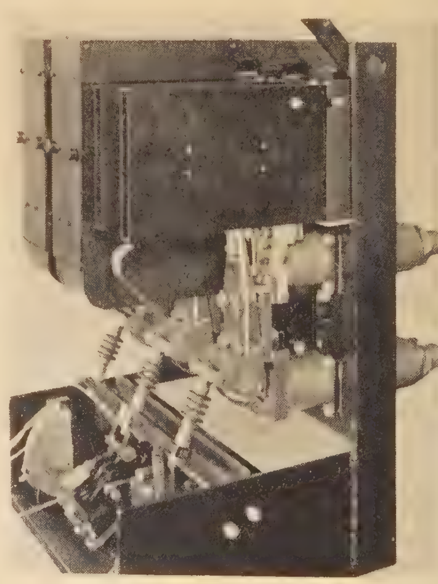

Figure 2. A right view of a 2,000-ampere magnetic De-ion breaker for 2,500–5,000-volt service

Rated interrupting capacity 150,000 kva. Right-pole arc chamber removed

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L. R. Ludwig is division manager, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; R. H. Nau is with the same company.

to the arc path. During operation an arc is drawn between separating contacts, and is then magnetically moved toward the closed top of the slots in the insulating plates. At this position the presence of a strong magnetic field imparts to the electrons in the arc an upward component of velocity. They in turn bombard gas particles and produce an actual blast of gas perpendicular to the arc, which action requires the arc continuously to ionize fresh gas in considerable quantities. When current zero is reached this action continues in a sufficient degree effectively to deionize the plurality of short lengths of the arc near the edges of the plates. Dielectric strength is consequently established.

The insulating plates are made of a material which does not form gases in order to prevent unnecessary display of ionized flame in the air space above the interrupting chamber. Flame from the arc core must pass upward between the closely spaced plates for a distance of several inches before reaching free air space. During this passage contact with the cool walls of insulating material deionizes the flame so that upon reaching the free air space beyond the chamber there is no danger of external flashover of the arc chamber or to metal parts of the enclosure in which the breaker is mounted.

Figure 4 (left). Oscillogram of a 1,900-volt 39,000-ampere rms single-phase interruption

A—Arc voltage measured at breaker terminals

B—Travel record

C—Current through breaker

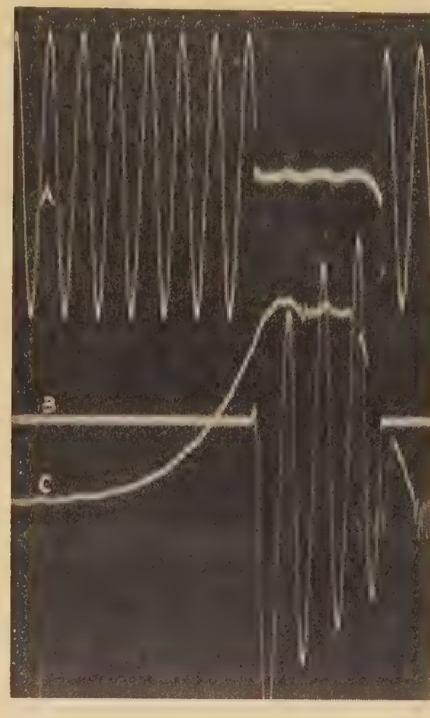


Figure 5 (right). Oscillogram of a "closing-opening" single-phase interruption with 1,800 volts and 38,500 amperes rms

A—Voltage at breaker terminals

B—Current through breaker

C—Travel record

This principle of deionization is applicable to a wide range of voltage. The magnetic-field strength, thickness of the plates and the space between the plates, and the shape of the slot determines the volts per plate at which a given current can be interrupted. The number of plates used may be suitably chosen along with the other parameters to make the interrupter adequate for specified current and voltage ratings.

In the case of the 600-volt air breaker previously described[4] sufficient field strength to give the required volts per plate was obtained by the use of iron plates built in above the insulating plates and in the same plane with them. However, for the higher-voltage circuits iron has been added in the form of a laminated structure about the chamber, and a multi-turn coil is connected to provide a very intense field. The iron structure is shown diagrammatically in figure 1.

The figure also shows an outline of one of the deionizing plates. The slot into which the arc is forced by the magnetic field is long and quite narrow at the top. When the current in the arc is high during most of the half cycle preceding interruption, the arc cannot reside in the uppermost portion of the slot because the cross-sectional area required by its core is large compared to that available in the upper slot region. The effect of this construction is to permit the arc to operate with a low voltage drop until just prior to current zero, and thus the energy dissipated in the

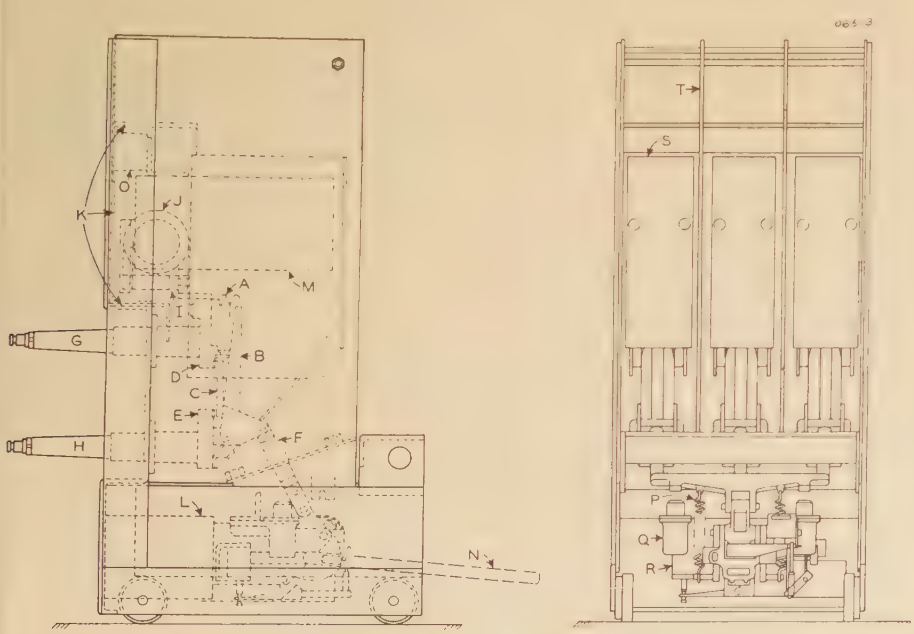
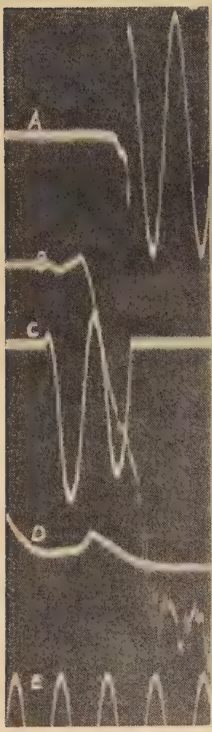


Figure 3. Front and side views of the new De-ion circuit breaker for 150,000 kva interrupting capacity

A—Arcing- and secondary-contact platform
B—Moving-contact arm
C—Main-contact bridge member
D—Upper contact stud
E—Lower contact stud
F—Insulating push rod
G—Upper stud bushing
H—Lower stud bushing
I—Male adapter of magnet coil which engages the female connector of the panel-end horn of the arc chamber
J—Magnet coil
K—Panel barriers
L—Solenoid mechanism
M—Magnet shoes
N—Removable operating handle
O—Insulating magnet bushing
P—Accelerating spring
Q—Air dash pot
R—Shunt trip
S—Removable arc chamber
T—Interphase barriers

interruption is reduced. The arc voltage, as shown on the oscillograms in figures 4 to 9, indicates the effectiveness of the slot design in limiting the arc voltage. The design of the slot differs from that of lower-voltage breakers which are also applied for d-c interruption.



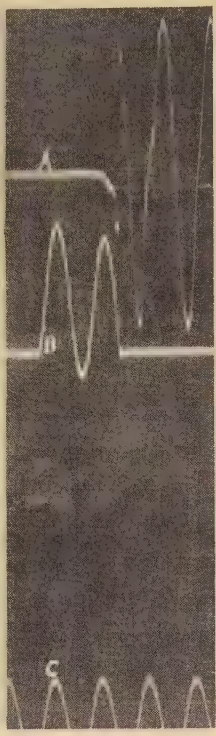


Figure 6 (left). Oscillogram of a 3,000-volt 27,500-ampere-rms single-phase interruption

A—Arc voltage measured at breaker terminals
B—Travel record
C—Current through breaker
D—Shunt-trip-coil current
E—60-cycle timing wave

Figure 7 (right). Oscillogram of a 4,000-volt 22,000-ampere-rms single-phase interruption

A—Arc voltage measured at breaker terminals
B—Current through breaker
C—60-cycle timing wave

Plates approximately one-eighth inch thick are found experimentally to be most suitable. The space between the plates may be varied from one-eighth to one-fourth inch, depending on the magnitude of the current to be interrupted and the voltage. An arc length of $9^1/_2$ inches between horns at the two ends of the chamber is sufficient for interruption of 150,000 kva at either 2,300 or 5,000 volts. Rms voltages as high as 550 volts per inch or 140 volts per plate have been interrupted when the short-circuit current was approximately 22,000 amperes. An interrupting device of this type remains substantially constant in kilovolt-amperes and it is found that higher currents can be opened at lower voltages or that higher voltages can be cleared satisfactorily if the current is less.

In order to make all plates effective in the longer chutes for the higher circuit voltages, arcing horns are necessary at both ends of the chamber. These consist of copper bars placed vertically at each end of the chute. The lower terminals of the panel-end horn are sloped toward the arcing contacts of the breaker to facilitate transfer of the arc to them. The horns are slotted to release gas pressure which would tend to prevent intimate contact between the arc and the horn at the moment of transfer. The multiturn coil at one end of the chute is electrically connected between the arcing contact at that end and the horn. Therefore, the coil does not pass current except after the contacts have parted and the arc terminal has transferred to the horn, thus introducing the coil into the circuit.

Air-Breaker Construction

Breakers for 150,000 kva can be constructed in such reasonable dimensions that one can be mounted above another if desired, and therefore the draw-out type of design is particularly advantageous. The fabricated steel frame, as shown in figure 2 and figure 3, serves to support the four component subassemblies of the breaker, and has wheels attached at the bottom for withdrawal from a metal cubicle. The subassemblies are the contact structure, electric mechanism, arc chutes, and barrier system.

The contact structure of an air breaker has two functions to perform, that of carrying the load current and of drawing the arc which serves as the interrupting element. It is important to segregate these functions carefully in order to save the current-carrying or main contacts from any effects of the arcing. Also, the interrupting or arcing contacts must be designed to withstand the magnetic and thermal stresses placed on them. The main contacts are self-aligning bridge members of copper and the actual contact is made between bars of silver-nickel composition brazed to copper. The lower main contact is protected from arcing by a parallel shunt. The upper main contact is shunted by both secondary and arcing contacts which open in turn after the main contacts have parted. A horizontal overlapping barrier system isolates the main contacts from gases thrown downward by the arc.

The necessary relative motion between the two upper contacts and the main contacts is obtained by limited travel of the upper contacts on the stationary-contact side of the switch. The upper contact springs are enclosed by a platform member which has limited travel, and are thereby well protected from burning. An inverted U shunt is also enclosed within this platform member and is designed so that the magnetic force set up by the short-circuit current presses the secondary contacts tightly together in addition

Figure 8 (left). An oscillogram of a three-phase interruption at 2,300 volts, 124,000 kva

A—Travel record
B—Arc voltage of phase 1 to neutral, 1,640 volts
C—Shunt-trip-coil current
D—Breaker current of phase 1, 27,500 amperes rms
E—Arc voltage of phase 2 to neutral, 1,640 volts
F—Breaker current of phase 2, 39,000 amperes rms
G—Arc voltage of phase 3 to neutral, 1,640 volts
H—Breaker current of phase 3, 26,000 amperes rms

Figure 9 (right). Representative oscillogram of a low-current shot on a single pole at 2,300 volts, 630 amperes rms

A—60-cycle timing wave
B—Arc voltage across breaker terminals
C—Current through breaker
D—Travel record
E—Shunt-trip-coil current
F—Indicator wave

to the springs. Parallel-path protection is thus provided for the main contacts to prevent them from opening any portion of the interrupted current. Tungsten-alloy contacts are provided for the secondaries and arcing tips.

Insulation of the contact structure and mechanical support is obtained by Micarta bushings through which the electrical connection is carried to the rear of the breaker.

The electric operating mechanism together with trip-free levers comprises a unit which is mounted horizontally in the

Figure 10. Arc chamber which was used during 27 interruptions at maximum short-circuit currents and also for 76 interruptions at currents of 14,000 amperes and below. The insulating plates are in satisfactory condition for further service

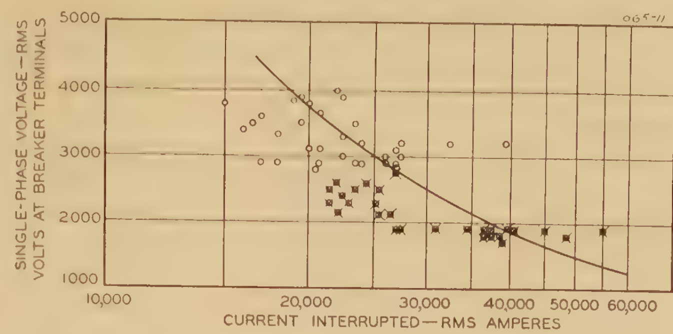
base of the breaker. The mechanism actuates a cross bar which is mechanically connected to each moving contact arm by an insulating operating rod. The principal advantage of the mechanical construction is high speed, which results in only a half cycle of arcing at most currents.

The arc chamber previously described is withdrawn from the breaker by pulling forward and using the laminated iron field structure as a support.

The function of the barrier system is to isolate electrically the live phases from each other and from the metal enclosures, and the rms current interrupted was 38,500 amperes.

Figure 6 shows the interruption of 27,500 amperes rms at 3,000 volts single phase. In figure 7, the interruption of 22,000 amperes rms at 4,000 volts single phase is illustrated. Both oscillograms show less than a half cycle of arcing.

Figure 11. Magnetic De-ion circuit breaker single-pole interruption tests



Crosses indicate tests made on a single arc chamber whose insulating plates were spaced one-fourth inch apart

Circles indicate tests made on a similar arc chamber whose insulating plates were spaced one-eighth inch apart

particularly during the interrupting period when free ionized flame tends to expedite flashover. Obviously, the requirements of the barrier system are lessened if the interrupting chamber is made efficient so that only a small quantity of flame is allowed to escape. An enclosed space is provided by the barrier system above each arc chamber for the discharge of hot gases, which would otherwise build up pressure above the arc in the chute and hinder its interrupting ability. In this space the gases mix with cool air, and residual flame is suppressed. Muffling action is also secured by the barriered space. The barrier structure is built as a unit of insulating material and is supported from the breaker frame at the top.

Test Results

Interrupting tests have been made on the breaker through a voltage range of 1,900 to 4,000 volts single phase, using the maximum plant capacity of the Westinghouse high-power laboratory. Figure 4 is an oscillogram showing the interruption of 39,000 amperes rms at 1,900 volts across one pole of the breaker. The equivalent three-phase kva is 150,000. The voltage element connected across the breaker terminals shows that the arc drop remains comparatively low until nearly the end of the single half cycle of arcing.

Figure 5 shows a closing-opening operation at the same voltage and with the same plant setting. The crest value of the current following closure was 89,000 amperes,

A three-phase interruption record is illustrated in figure 8. The line-to-line potential in this case was 2,300 volts. The total kilovolt-amperes interrupted was 124,000, and the rms current opened by the center phase was 39,000 amperes rms. This test was made with the breaker completely enclosed in a metal cubicle which was at ground potential. Demonstration such as flame was entirely absent, and noise was at an acceptably low level.

Interrupting tests have been made throughout the current range with 2,300 volts across a single pole. The time of interruption increased to 20 cycles at 22 amperes, and then decreased to one-half cycle at 9 amperes. All interrupting tests were made with only reactance in the circuit, and consequently at low power factor. The typical oscillogram of figure 9 shows an interruption of 630 amperes rms at 2,300 volts single phase.

The arc chamber is not damaged by high-current short circuits. Figure 10 shows a photograph looking up into an arc chamber which had been used during 27 interruptions at the maximum short-circuit current of the laboratory, and in addition 76 interruptions of currents of 14,000 amperes and below at 2,300 volts single phase. The oscillograms of figures 4, 5, and 9 and phase three of figure 8 were made using this De-ion chamber.

In figure 11 points are plotted to semilog scale of currents interrupted at various single-phase voltages. Sixty-one test points are shown, based on currents inter-

rupted up to 55,000 amperes rms at 1,900 volts, and voltages as high as 4,000 volts, single phase. A curve corresponding to 150,000 kva is also drawn, and the number of successful operations above the curve and throughout the voltage range indicate a good margin of safety in the breaker over this rating. This figure also indicates that the kilovolt-amperes which can be interrupted is substantially constant from 1,900 to 4,000 volts, single phase.

The crossed circles of figure 11 are indicative of the previously noted 27 interruptions at the maximum short-circuit current of the laboratory. These tests as well as the 76 interruptions of currents ranging from 9 to 14,000 amperes rms were made on an arc chamber with one-fourth-inch spacing between the insulating plates, figure 10. The 34 circled interruptions of figure 11 were made on this arc chamber using similar insulating plates spaced one-eighth inch apart.

Conclusions

The high efficacy of the new De-ion circuit breaker to function at and above 150,000 kva with 2,500 to 5,000 volts demonstrates the practicability of the interrupter utilizing a gas blast which is produced by means of an intense transverse magnetic field. This interrupter is particularly desirable because the noise and demonstration usually found in air-circuit-breaker practice is greatly reduced. The ionized gases and other by-products of arc interruption are sufficiently controlled by the interrupter that unusual barrier arrangements are not needed. The new De-ion air circuit breaker is a particularly compact and sturdy device for use in modern clad switchgear, or for separate mounting.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Design and Construction of High-Capacity Air-Blast Circuit Breakers

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NONMEMBER AIEE

THE air-blast principle of circuit interruption is a recent introduction to the United States, although interrupting devices utilizing compressed air have been available in Europe for a number of years. The service performance of European breakers has been satisfactory, but inherent limitations prevented adoption in this country where large values of fault current and high rates of rise of recovery voltage are the rule rather than the exception. Exhaustive tests on forms of available air breakers heretofore available have shown that approximately 40,000 amperes represents the maximum current that can be safely interrupted at generator voltage, and then only under conditions of moderate rate of rise of recovery voltage. This fact alone made it essential, if air breakers were to be utilized, to develop an entirely different type, since applications in this country have commonly required oil breakers with interrupting ratings up to 60,000 amperes at 15 kv. Even this value of current does not represent the maximum requirement, since an increasingly strong demand exists for ratings at least up to 100,000 amperes at 15 kv or 2,500,000 kva.

It was believed that the principle of arc interruption by means of compressed air was sound, particularly for the higher interrupting ratings, so a development program was undertaken to overcome the previous limitations. Breakers with interrupting ratings as high as 1,500,000 kva (60,000 amperes at 15 kv) have already been built and tested, and design tests have been made which assure the availability of breakers of higher ratings when required by the industry. Two breakers rated 500,000 kva have been in service since early in November 1939, on the Consolidated Edison system. A number of 250,000-kva breakers of this same general type have been supplied for use on systems of the American Gas and Electric Company.

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Theory of Operation

The principle of interruption of the air-blast breaker is similar in many respects to the principles that have been thoroughly substantiated by both service experience and factory test with the oil-blast breaker. Fundamentally the theoretical basis of operation of the breaker is the displacement of the arc stream and the replacement of the arc products with insulation at a rate which will prevent break down of the dielectric by the recovery voltage. As applied to the air-blast breaker a stream of air under pressure displaces the arc stream and at the zero point of the current wave, purges the interrupting chamber of the hot gases. The flow of air across the separating contacts then provides the necessary dielectric strength at the required rate to prevent breakdown by the recovery voltage. A more complete exposition of this theory as applied to the air-blast breaker is contained in a companion paper by Messrs. Prince, Henley, and Rankin (*Transactions pages 510–17*).

Design Features

The actual design features of the breaker may be broken down into four major components in order to facilitate description:

1. Arc chute and movable contact
2. Air-blast valve
3. Operating mechanism
4. Control valve

The arc chute is a box structure of simple, compact design combined with great mechanical strength. Within this structure are the interrupting chamber, stationary contacts, cooling plates, arc barriers, and exhaust vent. Figure 1 illustrates the arrangement of the various parts of a typical chute designed for a 15-kv breaker with an interrupting rating of 500,000 kva. This chute is mounted in the breaker cell on porcelain insulators, and arranged to be easily removable for inspection.

The section at the right containing the fixed contacts, is the chamber in which the actual interruption of the arc occurs. The sides consist of blocks of insulation material with a contour designed to force the blast of air directly across the arc stream. A false top barrier containing an opening with relatively small clearances, through which the movable contact passes, forms the top while the back plate of the arc chute is also the back of the interrupting chamber and contains the entrance orifice for the air blast. The fixed-contact assembly is at the bottom of the chute, centrally located between the two insulating blocks.

Arc barriers placed at the exit of the interrupting chamber divide this portion of the interior of the chute into four passages each equipped with cooling plates. A fifth passage which also contains a cooler exists between the false and actual top barriers. All of these passages exhaust into a vertical vent where additional cooling members are installed.

The orifice in the back plate of the arc chute is located so that the normal flow of air is directly across the fixed contacts and in the plane of the longitudinal axis of the tips of the fingers. This flow of air forces the arc between the streamlined side members of the interrupting chamber and into the exit passages at the front of the chamber. In order to obtain short arc duration and minimum deterioration of parts, approximately 15 cubic feet of free air at 150 pounds initial pressure are required for a closing-opening operation on a triple-pole 15-kv 500,000-kva breaker while a 1,500,000-kva breaker requires approximately 25 cubic feet for such an operation.

The arc barriers are for the purpose of cutting the arc into sections and securing a maximum rate of increase in dielectric strength of the arc path. These barriers are of different thickness in order to equalize deterioration under the various interrupting conditions within the rating of the arc chute. The area of the passage enclosed by the barrier is proportional to the current to be interrupted while the number of passages is determined by the maximum rate of rise of recovery voltage. For 15-kv applications, tests have shown that normal interruptions up to full rating usually utilize only the first passage. The additional passages provide adequate factors of safety where high rates of rise of recovery voltage may be encountered and for that reason three barriers are used in the 15-kv arc chutes to form four exhaust passages.

The coolers are composed of stacks of thin copper plates located in the plane of the exhaust. These perform the function of cooling the exhaust gas to a point where it will not cause restrike on the outgoing side of the chute. The size and number of these stacks are determined by the current-interrupting rating.

The passage above the false top barrier allows the moving contact to be withdrawn without the external discharge of hot gases. It provides a chamber in which the time for the contact to pass through is sufficiently long to permit the air flow to completely purge the arc chute following circuit interruption, before uncovering the opening in the top barrier. The action within the section formed by the false and top barriers provides what is in effect a turbulent seal to prevent discharge around the moving contact without the necessity of a complex mechanical seal. The moving contact then finishes its stroke at which time it is completely withdrawn from the arc chute, thus providing the positive insulation of a clear air-break distance between open contacts. This also facilitates contact inspection, since the blade and its arcing tip are readily visible from the front of the cell when the breaker is open.

The exhaust gases are collected in a vent pipe of insulation material, where they are permitted to further cool and expand. Complete cooling and elimination of objectionable noise are assured by the final set of cooling plates located at the upper end of the vent pipe, where discharge takes place in the open air.

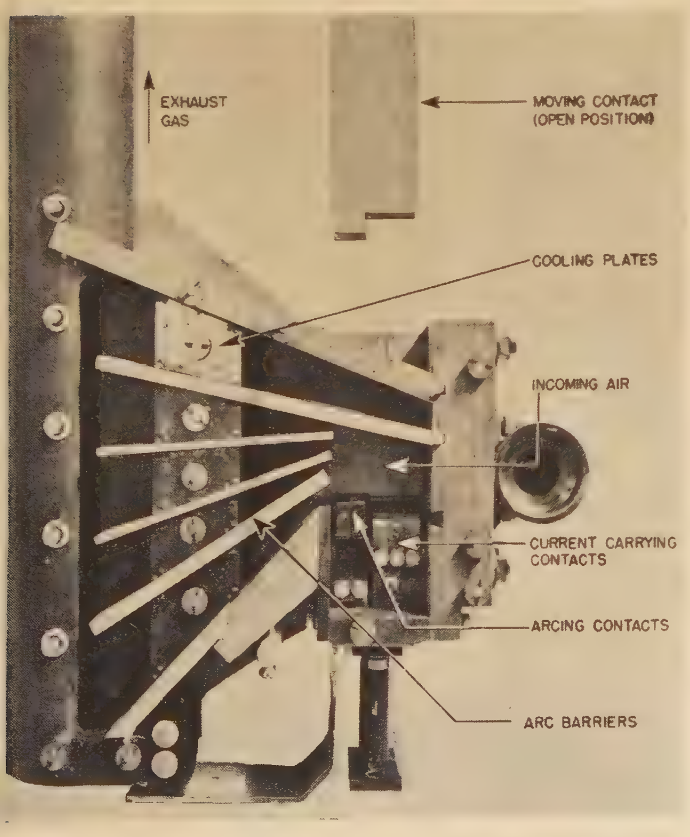

Figure 1. Cross section of arc chute of 500,000-kva breaker

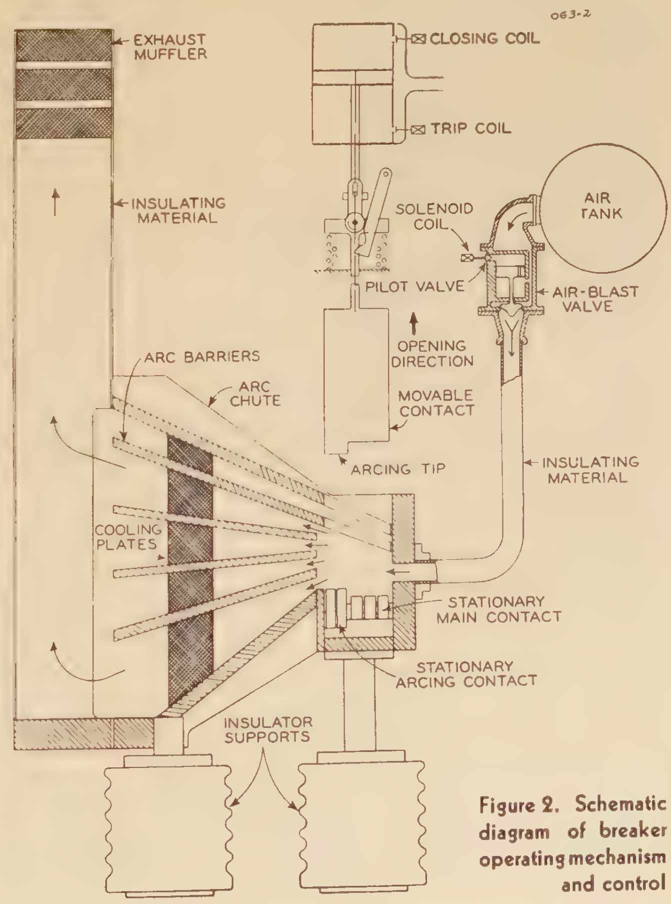

Figure 2. Schematic diagram of breaker operating mechanism and control

The stationary contacts consist of a suitable number of primary fingers to carry the normal rated current without excessive heating and secondary fingers consistent with the maximum current to be interrupted. The primary fingers are of the short-wipe line-contact silver-surfaced type that have been employed on various types of oil breakers for a number of years. These fingers are spring loaded with one end in contact with the stationary block and the other in contact with the movable blade, assuring a high-pressure silver-to-silver connection with the complete elimination of flexible shunts.

The secondary contacts consist of heavy copper fingers, surfaced on the burning area with a silver-tungsten alloy to minimize deterioration and prolong the life of the entire stationary contact assembly. These fingers are provided with a copper shunt to eliminate burning caused by vibration at the instant the movable blade engages the stationary contact, and facilitates current transfer on the opening operation. The secondary fingers are arranged to engage first and break last and, thereby, prevent burning on the primary contacts. An arcing plate has been incorporated in the design to further increase the number of interruptions that can be obtained without seriously deteriorating the stationary contacts. The burning surfaces of this plate are surfaced with a silver-tungsten alloy and are so placed that the arc is immediately transferred to it by the blast of air so the majority of the arcing occurs at this point instead of on the secondary fingers. All of these contacts and the stationary arcing plate are mounted as a unit assembly, which is easily removable from the chute for inspection or renewal.

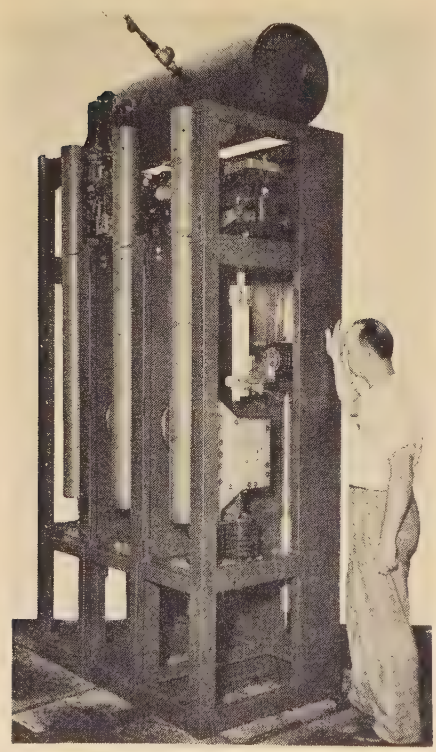

Figure 3. Typical 500,000-kva breaker complete in steel cell

The movable contact is a flat blade of copper, completely silver-surfaced, and equipped with a silver-tungsten alloy arcing tip. Silver-surfaced fingers, similar to the primary fingers, are mounted on the movable contact guide to provide a connection between the blade and entrance bushing. This method of making connections between movable and stationary current-carrying members is simple and compact, eliminating flexible leads or pigtails. Adequate tests have proved it to be satisfactory under all possible operating conditions.

In order to arrive at a satisfactory design of arc chute, numerous tests were made on various configurations and in many cases the action that takes place within the chute during interruption, was photographed.* The following description of the operation is, therefore, based on analysis of these high-speed photographs, as well as magnetic and cathode-ray oscillograms, which studied jointly, were of considerable aid in understanding the underlying theory and actual operation of the air-blast breaker.

Air, at a tank pressure of 150 pounds gauge, is introduced into the interrupting chamber through an orifice in the back plate of the arc chute and is so timed as to be present just prior to the parting of the contacts. The direction of flow of air is controlled by the contour of the interrupting chamber which also confines the arc to a definite path. Under this controlling condition, the flow of air forces the lower root of the arc from the tips of the secondary fingers to the surface of the arcing plate and is effectively prevented from restriking on the finger contacts by the positive flow of air. Arcing occurs on the secondary fingers for only a small fraction of the total arcing time and it is, therefore, possible to form a very accurate estimate of the condition of the stationary contacts from an inspection of the movable blade, which is fully exposed when the breaker is in the open position.

As the contacts move further apart the arc is forced into the first passage of the chute and lengthens rapidly. At the first current zero the stream of air removes the heated gases from between the contacts, placing a stream of clean air under pressure across the normal arc path. If the separation of contacts is sufficient for the dielectric strength of the air to withstand the recovery voltage, the arc has been successfully cleared. Inasmuch as the air in the interrupting chamber is under pressure, its dielectric strength is considerably greater than under normal atmospheric conditions and is sufficient to prevent restriking of the arc with only a short separation of the contacts.

If the contact separation at the first current zero has not been great enough to withstand the recovery voltage, the arc restrikes and interruption will occur at the next current zero. As the contact separation increases, additional barriers are brought into action forcing the arc to follow a path of rapidly increasing length. The speed of separation of the contacts is approximately three inches per cycle during this part of the stroke and by the second current zero from parting of the contacts, the separation is adequate to prevent the recovery voltage from causing the arc to restrike.

The movable contact is finally completely withdrawn from the chute, and during its passage through the last section, the gases are swept from the arc chute, and the air blast is shut off before uncovering the opening in the top barrier.

During the closing operation a blast of air is started across the contacts just prior to the time they meet. This very effectively prevents the arc from striking on the current-carrying parts and sweeps clear of the chute any gases which may be formed when the arcing contacts meet.

Blast Valve

For the arc chute to function properly, it is essential that a reliable valve be used to control the admission of the air blast. A high-speed differential-type solenoid-pilot operated valve has been designed for this purpose. The valve consists essentially of a bronze body with integrally cored air passages, a piston-operated main valve, and a solenoid-operated pilot valve. Poppet-type valves in conjunction with moderately soft seats have been utilized for their simplicity, speed of operation, and low leakage factor. It is of primary importance that the pressure drop of the valve be kept as low as possible and every effort has been made to provide a straight-line flow with a minimum of obstructions. Under intermittent flow conditions at a rate of 7,800 cubic feet of free air per minute, the pressure drop through this valve

* "The Cross-Air-Blast Circuit Breaker", D. C. Prince, W. K. Rankin, and J. A. Henley, *Transactions pages 510–17.*

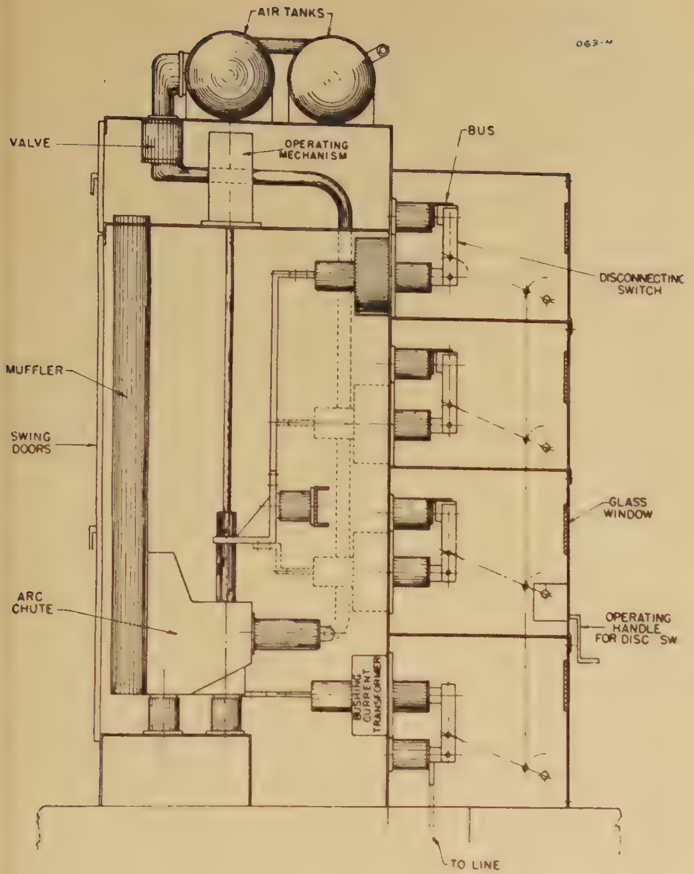

Figure 4. Application of air-blast breaker to metal-enclosed cubicle arrangement, complete with bus, disconnecting switches, and current transformers

is only about 10 pounds with an initial tank pressure of 150 pounds gauge. High speed of operation has also been obtained as the over-all operating time, from energizing the pilot valve control to complete opening of the main valve, is less than 2 cycles on a 60-cycle basis.

The blast valve is opened by energizing a solenoid, unbalancing a spring-loaded pilot valve. This allows the air to escape from above the piston at a greater rate than can be supplied by a small bleed hole from the high-pressure system. The unbalance in pressure on the two sides of the piston causes the piston to move, lifting the main valve from its seat. At the end of the piston stroke a small valve in the piston face is automatically opened, permitting a rapid flow of air to the area above the piston, but not sufficient to influence the operation as long as the pilot valve is open. This arrangement assures rapid closing of the pilot valve. With the valve in the closed position, the air under pressure holds it closed and prevents leakage.

Operating Mechanism

Mechanical operation of the contacts of this breaker is by means of a pneumatic mechanism, utilizing air pressure for both the closing and opening strokes.

Essentially the operating mechanism consists of two units, a double-ended driving cylinder and a straight-line linkage mechanism. Figure 2 shows a schematic diagram of the mechanism and control-valve equipment. The piston is directly connected to the straight-line linkage mechanism through a pair of slotted links which permit a short stroke of the piston before motion is transmitted to the contacts. To close, air pressure is applied to one end of the cylinder until the breaker is completely closed and latched in this position by a prop. On completion of the stroke, a mechanically operated switch opens to de-energize the closing control-valve solenoid.

The blast of air on closing is controlled by an interlock switch which both energizes and de-energizes the solenoid on the blast valve pilot at a predetermined point in the stroke.

The opening operation is practically the reverse of the closing operation. Air is applied to the opening side of the piston, and the first part of the motion provided by the slotted link arrangement is utilized to remove the latch. The accelerating springs rapidly bring the movable contact up to speed which is maintained by the air pressure until the blade passes the false barrier in the arc chute. At this point motion is decelerated by the action of a special dashpot, before allowing the operation to be completed. As in the case of the closing operation, air completes the opening stroke and is then cut off by a mechanically operated switch.

At the point where the blade is passing through the last section in the arc chute, an interlock switch opens to de-energize the blast of air. The mechanically operated switches used in the control of the mechanism and blast valve are directly

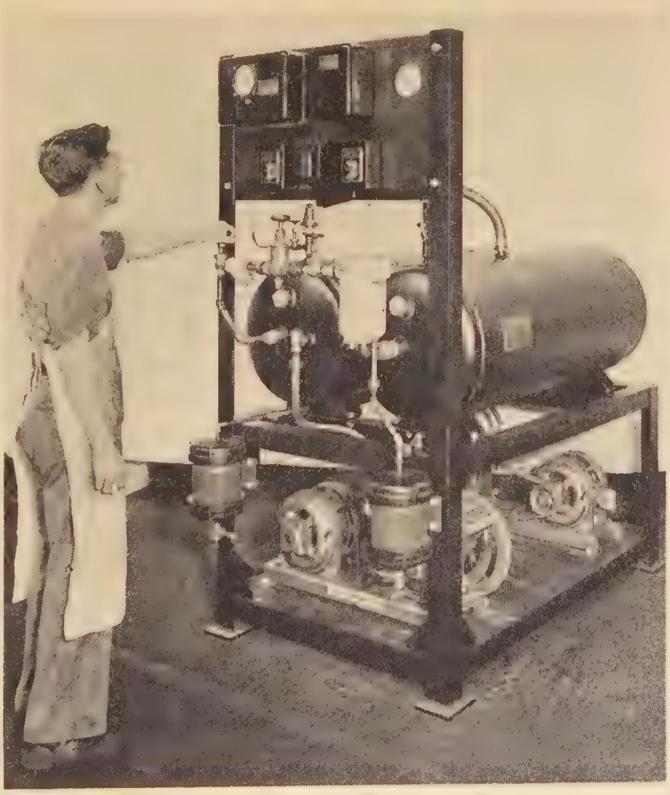

Figure 5. Typical compressor equipment for battery of 12 500,000-kva breakers

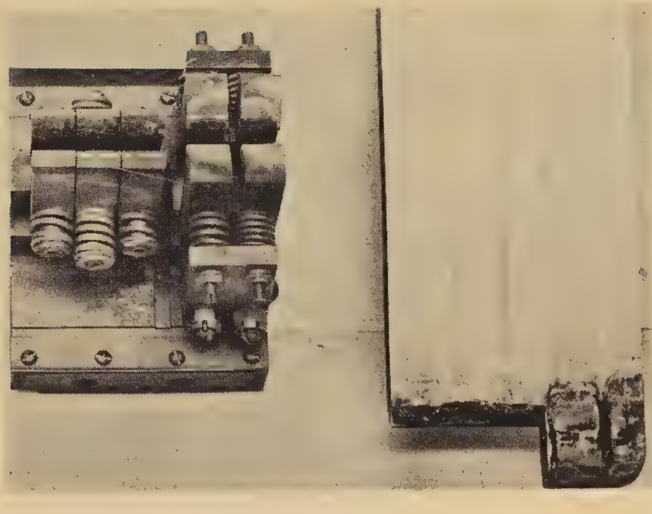

Figure 6. Condition of stationary and movable contacts following test

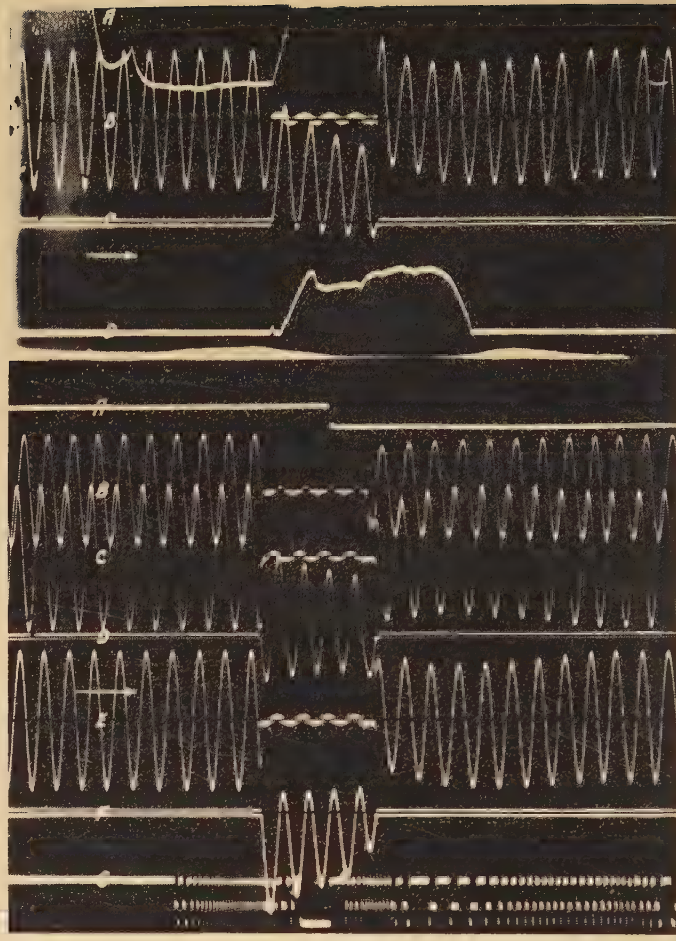

Figure 7 (right). Oscillogram of three-phase closing-opening test, interrupting 680,000 kva at 14,500 volts

connected to the mechanism. They are easily and accurately adjusted by movable cam surfaces and are of a simple and rugged construction.

Control Valves

On closing the operation is controlled by energizing the closing control-valve solenoid to admit air to the closing end of the cylinder after which the remainder of the operation is performed automatically by the sealing-in circuits and interlock switches. The opening stroke is initiated by energizing the blast-valve pilot since it is of primary importance to insure air being present at the contacts at the time of their parting. The blast-valve control is energized and motion of this valve actuates the valve which admits air to the opening side of the piston after which the control is handled automatically in the same manner as on the closing stroke.

The control valves used in conjunction with the mechanism are of the spring-biased poppet type with soft seats to minimize leakage. In order to prevent a false operation of the mechanism in case leakage does occur, the valves are so arranged that the passage to the cylinder is open to the atmosphere when the valves are in the closed position.

The closing and opening valves are interlocked in such a manner that the opening valve takes precedence over the closing valve under all conditions and provides the necessary trip-free operation of the mechanism. The operating mechanism is, therefore, fully trip free since an opening operation may be initiated at any time during the closing stroke.

General Arrangement

Figure 3 shows a typical 500,000-kva breaker mounted in a steel cell, with both terminal connections located at the bottom, and with the mechanism and air storage tank mounted at the top. A bottom-and-back arrangement can also be made in this same type of structure. Conclusive tests have shown that the interrupting element of this breaker is insensitive to position; the contacts may be mounted horizontally with the blast either up or down, or the moving contact may be drawn downward. Therefore, where local structural conditions require, an arrangement may be made with the storage tank and mechanism at the bottom, and the terminals at the top or the top and back. Figure 4 shows the application of this breaker to a metal-enclosed cubicle complete with disconnecting switches, bus, and current transformers. This construction provides a ready means of interlocking the gang-operated disconnecting switches with the cell doors, to permit entrance to the breaker cells only when the parts are safely disconnected from both bus and line.

Air Supply

In the case of these high capacity breakers, each breaker will have its own individual air storage tank, containing a sufficient supply for two closing-opening operations at full interrupting rating. A central compressor and storage system may be located at any convenient remote point, and connected by a manifold and nonreturn valves to the breaker unit tanks. These nonreturn valves assure the retention of sufficient air at each breaker for two operations in the event of failure of the central system.

The size and nature of the central compressor and storage plant will be determined by the number of breakers to be supplied, and the probable frequency of operation. The 500,000-kva breaker uses only about 15 cubic feet of free air per round trip operation. In one typical installation of these breakers, compressors rated 5 cubic feet per minute are used. These are operated by two-horsepower motors so with both the main and auxiliary compressors connected to operate, their running time will be about $1^1/_2$ minutes per breaker operation. Figure 5 shows this compressor and storage equipment, adequate for 12 500,000-kva breakers, for average central-station service. Two 5-cubic-feet-per-minute compressors are used, either one or both of which may be selected to hold the primary tank pres-

sure automatically within selected limits.

For indoor service, the moisture content of the air is of concern only in so far as it might cause sticking of the valves, since it has no effect on the interrupting performance of this type of breaker. To secure the required degree of dryness in the air, therefore, this system compresses to 250 pounds pressure in the primary tank where the air is cooled, dropping most of the moisture content. An automatic reducing valve feeds the secondary tank at 150 pounds pressure with dry air, which has been found to have a dew point below zero degrees Fahrenheit, which is entirely safe for indoor service. In addition to the automatic pressure controls for the compressor motors, the usual water pumps, oil traps, and safety valves complete this part of the equipment.

Each individual breaker storage tank is equipped with a pressure switch, which at any predetermined low pressure can be arranged to perform one of three functions:

1. Sound an alarm
2. Trip the circuit breaker
3. Lock the breaker against tripping

The type of service on which the breaker is used, will generally determine which of the three alternatives should be selected. This switch is equipped with a manually operated by-pass, so that the operator may elect to trip the breaker to clear normal load current, which requires only very low air pressure, when the air in the tank might not be adequate for full interrupting rating performance.

Tests

A very comprehensive series of interrupting tests was brought to a climax in August 1939 by a demonstration of the 500,000-kva breaker to a large group of interested engineers, at the high-capacity testing station at Schenectady. The breaker was subjected to both opening and closing-opening tests over a range

Table II

Test Number	Duty	Current, Amperes: Maximum Loop: Peak Value	Current, Amperes: Maximum Loop: RMS Value	Current, Amperes: Initial in Arc, RMS	Kva, Three Phase	Cycles From Trip Impulse to Interruption	Arc Length (Cycles)
1	CO	166,000	98,000	44,000			0.80
		197,000	112,000	48,000	350,000	4.9	1.05
		105,000	68,000	48,000			0.45
2	O	163,000	97,000	78,000		3.8	0.70

from 10 per cent to 150 per cent of interrupting rating. Table I summarizes the results of these tests, indicating that the longest arcing time was 0.5 cycle and the longest breaker operating time 6.0 cycles.

Additional tests were made on this same breaker following this series, making a total of some 20 operations, 13 of which were at or above full rating. Following this complete series, the contacts shown in figure 6 were still in condition to permit making many more tests without attention.

Figure 7 is a typical oscillogram taken during this series of tests, and shows a three-phase closing-opening operation at 27,000 amperes, 14,500 volts, or slightly above full rating of the circuit breaker.

One of the unique features of this type of interrupting device is its high current-closing ability. The blast of air during the closing operation effectively delays the striking of the arc until the contacts have practically touched, and then promptly clears away the gases which are generated. Table II, test 1, shows the results of a typical three-phase closing-opening test at 4,200 volts in which the breaker successfully closed against a peak current of 197,000 amperes and then tripped and cleared. Test 2 was an opening test at 4,200 volts across a single-pole unit, in which the breaker cleared a current of 78,000 rms amperes, initial in arc.

In the course of making tests for design information, at reduced pressure levels, or with experimental timing of blast-valve opening with respect to contact separation, occasional operations were encountered when the breaker did not clear, and in due course of time the fault was removed by the station back-up breaker. In such cases arcing continued within the interrupting chamber, melting contact parts, and destroying some of the material of the arc chute. However, no damage resulted to the cell or enclosing structure, either by disruptive forces or by arcing. In all cases the breaker was again ready for service inside of two hours after merely replacing contact parts and barriers.

Conclusions

Oilless circuit breakers for indoor service are now available for the first time in interrupting ratings completely covering the range of oil breaker ratings. A number of high-capacity units has been placed in service, and a 1,500,000-kva 15-kv triple-pole unit has been built and completely tested. A review of the design and tests on the air-blast breaker brings out the following:

1. Complete elimination of fire hazard
2. Positive operation, with arcing time closely approaching the irreducible minimum
3. Contacts and arcing compartment built for long life, and minimum deterioration
4. Arcing contact exposed for ease of inspection
5. Flexibility of mounting arrangement, permitting either bottom, back, or top connections
6. Space requirements equal to, or less than correspondingly rated oil breakers, which is of importance in modernization of old stations or extensions of existing switchhouses
7. Simplicity and compactness of application to steel cubicle construction, which is easy to install, safely interlocked, and having all design features co-ordinated
8. High inherent current-closing ability

Table I. Three-Phase Tests at 14,500 Volts

Test Number	Duty	Current, Amperes Maximum Phase: Maximum Loop: Peak Value	Current, Amperes Maximum Phase: Maximum Loop: RMS Value	Current, Amperes Maximum Phase: Initial in Arc, RMS	Kva, Three Phase	Cycles From Trip Impulse to Interruption	Arc Length (Cycles)
1	O	4,400	2,800	2,100	53,000	5.0	0.05
2	O	12,000	7,000	5,400	135,000	5.4	0.1
3	O	32,000	19,500	13,500	340,000	5.0	0.05
4	O	48,000	29,000	19,000	480,000	5.8	0.2
5	O	55,000	32,000	25,000	630,000	5.9	0.3
6	CO	48,000	29,000	20,000	500,000	5.9	0.3
7	CO	80,000	49,000	29,000	730,000	6.0	0.5

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

A New 15-Kv Pneumatic Circuit Interrupter

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Synopsis: The demand for oilless circuit breakers of large interrupting capacity to meet the requirements of American practice directs attention toward an improved compressed-air circuit breaker which materially extends the present limitations as exemplified by continental designs.

A brief historical review of the trend toward oilless-circuit-breaker development is given. The comparison is made of the available methods of circuit interruption in air. The particular applicability of compressed air is stressed and a new circuit interrupter is described which can reach an interrupting capacity of 1,500,000 kva at 15,000 volts. Among the outstanding features of this interrupter are extremely high operating speed and rapid interruption with minimum energy dissipation. Test results are given indicating the adequacy of this type of design.

THE circuit-breaker art, almost from the time of its inception, has depended upon the use of oil as an interrupting medium in the larger and higher-voltage units. The choice of oil was based upon its excellent insulating properties and its remarkable arc-quenching ability. Oil, and its vapor, can be ignited, however, and thus can constitute a serious fire hazard, as the result of abnormal circuit-breaker operation. This factor has long been recognized, but practical operation of electrical systems has demonstrated that oil fires directly chargeable to circuit-breaker failures have been negligible. Recently, however, growing demand on the part of operators and development of the principles of oilless circuit interruption in Europe have combined to strengthen the interest in oilless circuit breakers in this country.

The first major contribution in the oilless breaker field was the development of the De-ion air breaker in 1928.[1,2] Prior to this time, air circuit breakers had been used for many years with unquestionable success in lower-voltage circuits in which limited interrupting capacity was sufficient. The De-ion breaker, however, interrupted an arc in air using entirely new principles and so efficiently that it has been constructed for voltages up to 23 kv and for interrupting capacities as high as 750,000 kva at 15 kv or 1,500,000 kva at 23 kv. Twenty-three kv is sufficient for virtually all indoor applications in this country. This breaker is completely self-contained and operates without an auxiliary air system or the need of a replenishable interrupting fluid.

Greater interrupting capacities are continuously being required, and the economic range of the De-ion breaker will not prove adequate for all requirements. For higher interrupting capacities to 1,500,000 kva at 15 kv other forms of oilless breakers take on new attractions.

The departure from oil in Europe began with the introduction of both compressed-air and water breakers in 1929 and 1930.[3–6] The new trend was accelerated there because of the high price of oil and

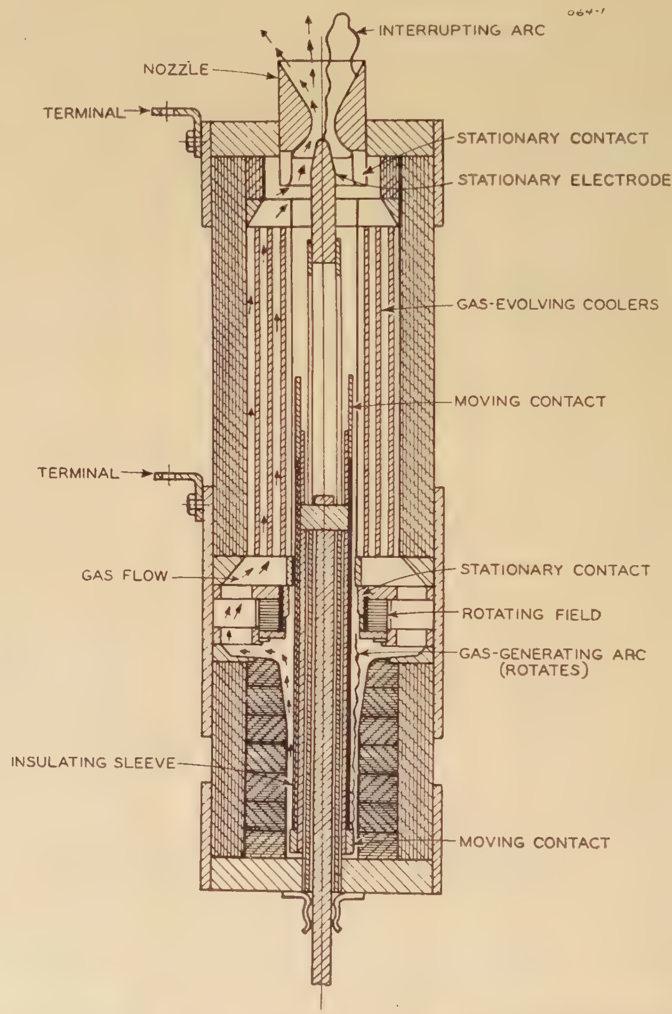

Figure 1. Self-generated-gas-blast circuit breaker (shown in open position)

Figure 2. Oscillogram of test on self-generated-gas-blast circuit breaker showing interruption of 30,000 amperes at 13.2 kv

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1. For all numbered references, see list at end of paper.

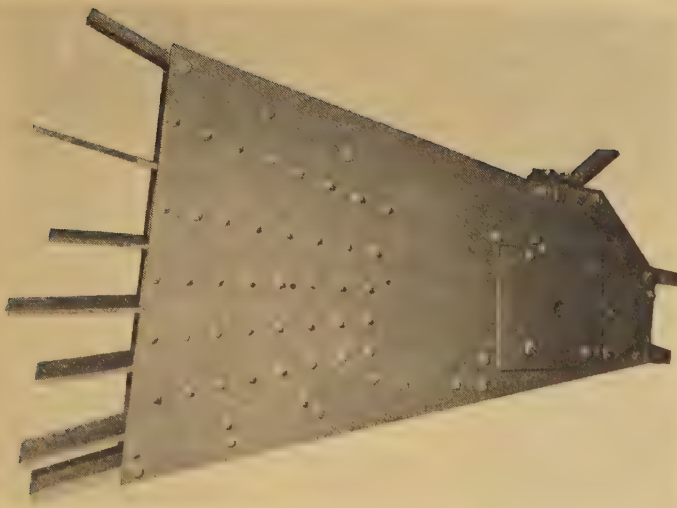


Figure 3. Experimental chute for compressed-air breaker

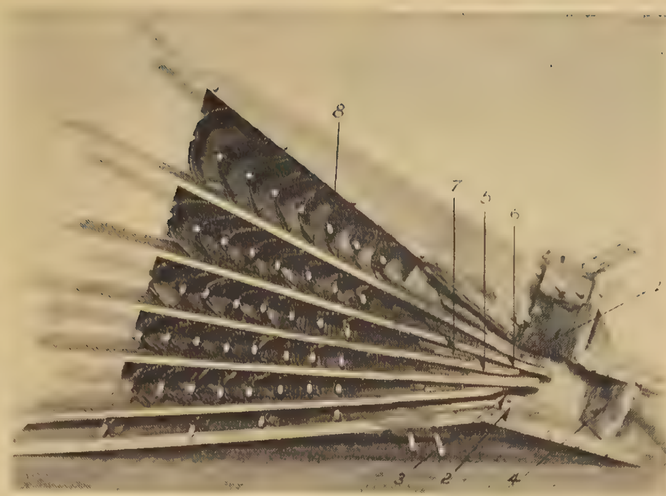


Figure 5. Experimental chute for compressed-air circuit breaker after extended series of tests

metals and because the limited capacities for which compressed air or water circuit breakers could then be built were sufficient to meet European requirements. Considerable development has been done in Europe with both types of breakers. The field of application of oilless breakers in Europe is becoming extensive and for some manufacturers is including the higher voltage and outdoor types.[7–9] In America, by contrast, the immediate demand is limited to indoor oilless breakers and although the European developments may influence the American trend, the more limited interrupting capacities which they find acceptable will not be sufficient to meet our requirements. This is especially true since European designs do not reach 1,000,000 kva, and American practice requires 1,500,000 kva or more at generator voltage.

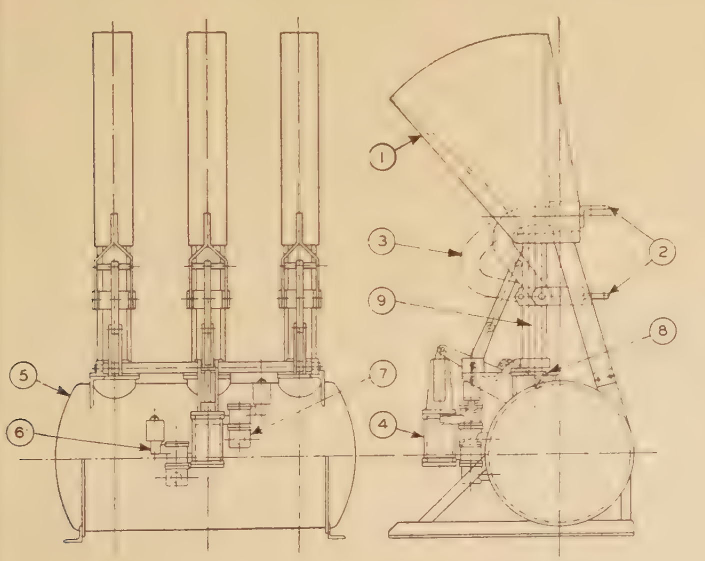


Figure 4. Compressed-air circuit breaker with vertical chute

1—Chutes
2—Terminals
3—Moving contacts
4—Operating cylinder
5—Storage tank
6—Closing valve
7—Opening valve
8—Air valve for chute
9—Insulated air tube

Comparison of Principles of Air Circuit Interruption

In choosing a suitable operating principle for application to air circuit interruption, an experimental review of available methods was made. The results of this review will be described to present the background of reasons for the choice of interrupter finally reached.

Compressed-Air Arc Extinction

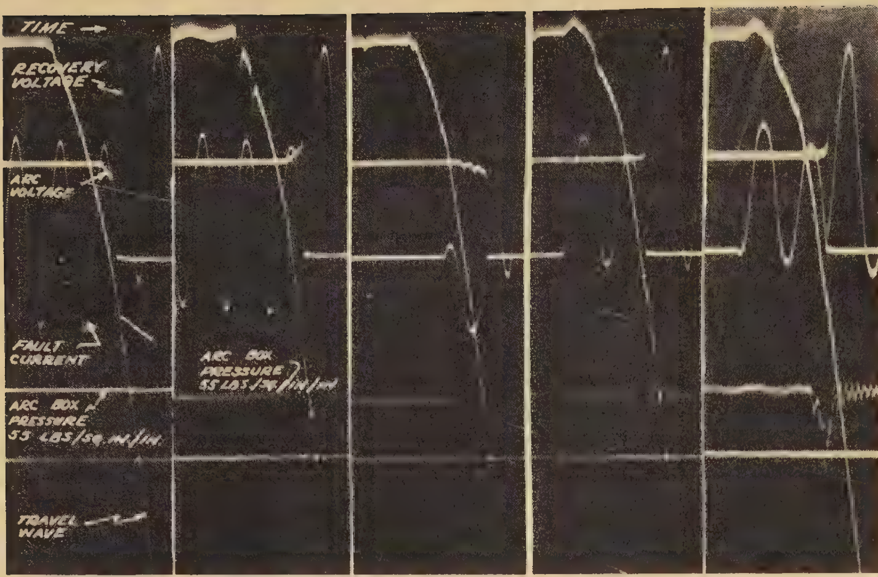
In Europe, variations of the nozzle type of interrupter have become most popular. They consist of an orifice through which an arc is drawn or blown and then subjected to a very intense longitudinal blast of air. For the lower ranges of current and at system capacities where the voltage recovery rate after arc extinction is not too great, this type of interrupter is quite satisfactory. As the current or voltage is increased the air requirements mount, until at 1,000,000 kva, pressures in excess of 200 pounds per square inch are required. The nozzle type of interrupter is, therefore, not appealing.

Self-Generated-Gas-Blast Breakers

In order to overcome the necessity of an external air-supply system, the blast of gas may be obtained by the decomposition of suitable materials. By selecting the proper material and arrangement, very high pressures of suitable gases may be obtained, and the energy to produce the gas pressure may be extracted from the arc itself during short circuit.

Boric-acid fuses and De-ion protector tubes are excellent examples of devices operating on this principle. In Europe, circuit breakers have been produced commercially where a synthetic resin is used for producing the gas blast.[12] Two self-generated-gas-blast breakers have been developed by the company with which the authors are associated—one utilizes boric-acid in close proximity to the arc-drawing contacts with suitable boric-acid-lined arc chutes into which the arc is driven by the expelled arc gases. The other is a two-arc interrupter as shown in figure 1. One arc is established through a conventional orifice and subjected to a longitudinal blast of gas in quite the same manner as used in continental compressed-air circuit breakers. The other arc is drawn in a space closely surrounded by gas-producing walls. This arc is not relied upon to supply interrupting ability except for low values of current, but to supply the gas blast for the first mentioned arc.

The interrupter consists of three essential elements—the lower part which houses one set of contacts, and the gas-forming elements; the central part which cools the hot gases and as a result of the



energy thus extracted, liberates more gas and eventually delivers the thoroughly cooled and deionized gas to the interrupting arc (which is located at the top of the interrupter) in such quantity and at suffi-

Table I. Opening Tests on an Experimental Compressed-Air Circuit Breaker

13.2 Kv Initial Voltage Applied to a Single-Pole Unit of a 15-Kv Circuit Breaker; 60 Cycles

Test Number	RMS Amperes Interrupted	Arcing Time (Cycles)	Recovery Voltage (Kv)	Air Pressure in Tank (Lbs/Sq In.)
1	1,390	0.505	12.7	105
*2	1,350	0.35	13.2	105
3	2,680	0.20	12.8	150
4	2,620	0.20	13.0	150
5	2,660	0.45	13.0	150
6	4,220	0.20	12.7	150
7	5,180	0.25	12.9	150
8	4,950	0.35	12.9	150
9	10,400	0.45	12.8	150
10	10,000	0.15	12.5	150
11	7,900	0.40	12.8	150
*12	12,700	0.40	12.4	150
13	16,300	0.25	12.8	150
14	16,600	0.10	12.7	150
15	19,800	0.60	12.7	150
16	23,000	0.45	12.7	150
17	22,600	0.35	12.8	150
18	28,700	0.615	12.8	150
*19	35,000	0.505	12.4	150
20	40,600	0.6	12.5	150
*21	47,800	0.15	12.7	150
*22	51,800	0.25	12.1	150
23	32,700	0.15	12.4	150
24	31,900	0.15	12.3	150
25	41,400	0.35	12.3	150
26	30,650	0.505	12.4	150
27	23,800	0.70	12.4	125
28	23,000	0.75	12.5	125
29	20,650	0.60	12.6	125
30	27,800	0.25	12.4	125
31	23,800	0.75	12.4	125
32	36,700	0.40	12.2	125
33	43,000	0.40	12.2	125
34	33,100	0.505	12.4	125

* Magnetic oscillograms of these tests are shown in figure 6.

Figure 6. Magnetic oscillograms from table I

Fault current (amperes)—from left to right:
1,350 12,700 35,000 47,800 51,800

Recovery voltage (kv)—from left to right:
13.2 12.4 12.4 12.7 12.1

ciently high pressure to handle very heavy currents.

In this type of design the gas-forming parts must be shaped to supply sufficient gas for interruption at low currents without having excessive gas generation and pressure at high currents. Since the gas is obtained from solid surfaces in proximity to an arc, repeated operations produce erosion that affects the amount of gas generation and the interrupting characteristics. These considerations, together with other factors, discouraged further work on this type of construction.

The interrupter has handled currents up to 48,000 amperes at 7.6 kv and to 30,000 amperes at 13.2 kv as shown by the oscillogram in figure 2. The arcing time for the high values of current usually did not exceed two half cycles yet pressures as high as 1,000 pounds per square inch were recorded. While this pressure may seem high, extrapolation from compressed-air requirements for this type of nozzle interrupter are quite comparable. The ratings desired, however, appear to be beyond the capacity which can be reached with this principle.

Magnetically Produced Air Blast

For many years magnetic fields have been used to extinguish arcs by blowing them into some type of arc chute which lengthens and constricts the arc. Recently a new means of effecting interruption with a magnetic field has been described.[3,4] An interrupter of this type consists of parallel insulating plates spaced apart and slotted at the lower end. The arc is driven into this slot by means of a magnetic field. When the arc reaches the upper portion of the slot the magnetic field exerts a force on the electrons in the gas stream and gives them a component of velocity transverse to the arc. These electrons in turn bombard neutral gas particles, with the final result that a blast of gas is caused to flow upward through the arc path. When current zero is reached this blast of gas effectively introduces a strong deionizing action at the end of the slot, which effectively extinguishes the arc.

Within the last two years two types of lower-voltage breakers have been developed using this interrupting principle. The first type was for 600 volts and below and the second for potentials of 2,500 and 5,000 volts. The lower-voltage devices have interrupted currents as high as 120,000 amperes and the 2,500-volt interrupter satisfactorily clears currents up to 50,000 amperes.

The effectiveness of this principle is not sufficient for the interruption of currents as high as 60,000 amperes at 15,000 volts.

Compressed-Air Interrupter

A more effective air stream can obviously be produced by utilizing compressed

Table II. Opening Tests on an Experimental Compressed-Air Circuit Breaker

13.2 Kv Initial Voltage Applied to a Single-Pole Unit of a 15-Kv Breaker; 60 Cycles

Test Number	RMS Amperes Interrupted	Arcing Time (Cycles)	Recovery Voltage (Kv)	Air Pressure in Tank (Lbs/Sq In.)
1	1,370	0.45	13.1	150
2	1,310	0.45	13.2	150
3	2,740	0.35	13.1	150
4	3,020	0.15	13.2	150
5	3,920	0.35	13.1	150
6	4,550	0.45	13.1	150
7	4,950	0.35	13.0	150
8	10,600	0.35	12.8	150
9	10,700	0.65	13.0	150
10	11,100	0.40	13.0	150
11, 12, 13	Approximately 12,000	No oscillogram		150
14	27,800	0.35	12.7	150
15	23,800	0.45	12.7	150
16	23,400	0.35	12.6	150
17	34,600	0.35	12.6	150
18	26,600	0.35	12.4	150
19	23,900	0.45	12.3	150
20	39,800	0.65	12.2	150
21	50,100	0.60	12.2	150
22	31,000	0.50	12.2	150
23	40,000	0.60	12.4	150
24	30,200	0.50	12.3	150
25	51,800	0.85	12.3	150

Table III. Opening and Closing-Opening Tests on an Experimental Compressed-Air Circuit Breaker

13.2 Kv Initial Voltage Applied to a Single-Pole Unit of a 15-Kv Circuit Breaker

Test Number	Operation	RMS Amperes Interrupted	Arcing Time (Cycles)	Recovery Voltage (Kv)	Air Pressure in Tank (Lbs/Sq In.)
1	O	1,380	1.1	13.0	150
2	O	1,280	0.5	13.3	150
3	O	2,890	0.3	13.2	150
4	O	3,440	0.3	13.2	150
5	O	2,690	0.3	13.1	150
6	O	4,660	0.2	13.2	150
7	O	4,460	0.3	13.1	150
*8	O	6,200	0.4	13.1	150
9	O	9,000	0.9	13.0	150
10	O	7,500	0.5	13.0	150
11	O	7,000	0.2	12.6	150
12	O	16,000	0.3	12.6	150
*13	O	15,800	0.3	12.7	150
14	O	9,600	0.7	12.8	150
15	O	20,600	0.6	12.4	150
16	O	23,400	0.6	12.6	150
17	O	22,800	0.7	12.2	150
*18	O	29,000	0.7	12.4	150
*19	O	40,000	0.4	12.6	150
20	O	40,600	0.4	12.5	150
21	O	44,400	0.4	12.0	150
22	O	44,400	0.6	12.5	150
23	CO	1,270	0.6	13.0	150
24	CO	1,280	0.7	13.1	150
25	CO	2,650	0.5	13.0	150
26	CO	2,530	0.5	13.0	150
27	CO	2,570	0.5	13.0	150
28	CO	4,320	0.6	13.0	150
29	CO	3,980	0.6	13.0	150
30	CO	4,260	0.6	13.0	150
31	CO	7,520	0.6	12.8	150
32	CO	7,520	0.6	12.8	150
33	CO	7,450	1.2	12.8	150
34	CO	11,300	0.3	12.6	150
35	CO	11,500	0.7	12.4	150
36	CO	17,000	0.3	12.0	150
37	CO	Approx. 20,000	No oscillogram	No oscillogram	150
38	CO	Approx. 20,000	No oscillogram	No oscillogram	150
39	CO	20,800	0.5	11.4	150
40	CO	Approx. 25,000	No oscillogram	No oscillogram	150
†41	CO	25,000	0.5	11.2	150
42	CO	27,500	0.6	11.3	150

*Magnetic oscillograms and cathode-ray oscillograms of these tests are shown in figures 7 and 8 respectively.

†Magnetic oscillogram of this test is shown in figure 9.

air in the type of arc chamber just described. In this case the magnetic field is no longer necessary. Tests were made with this structure which indicated greatly increased interrupting capacity. An external air-supply system must be provided of course, but in view of the extremely high interrupting ratings which can be achieved in very small space, the use of compressed air in conjunction with an arc chamber of the type described appeared to be the most feasible method of proceeding toward the design of a breaker having sufficient interrupting capacity to meet all indoor requirements. A comparison of the interrupting ability of a compressed-air device built in this manner, with known types of compressed-air breakers utilizing nozzles for interruption, indicated that an air stream perpendicular to the arc path in conjunction with insulating plates was much superior.

The contacts and surrounding walls are arranged so that the arc is blown by the air stream from its point of inception against suitable insulating splitters. There the arc remains practically stationary and substantially perpendicular to the gas blast throughout the arcing period. During this time the gas is allowed to escape around the sides of the arc, freely enough to prevent building up of pressure sufficient to interfere with the continuity of the arc stream and at the same time sweeps the excess ionization from around the arc out into the space beyond the splitters. Thus, as the current zero approaches, the residual ionization associated with previous high current has been removed without high arc voltage, and the time between current zero and restored voltage becomes adequate for interruption even though the voltage recovery rate is high.

The next important requirement is to cool and deionize the gases sufficiently before allowing them to escape beyond the splitters, to prevent flashover on the outside. Further cooling is necessary for the higher kilovolt-ampere ratings to prevent excessive external demonstration. Both of these problems are solved by suitable coolers and mufflers described later.

Aside from the considerations of intimate association of the gas pressure, arc behavior, and splitter performance, there are other practical reasons that favor the cross-blast type of construction over the longitudinal blast. These considerations are: (1) the ability with a blast of air directed at right angles to the direction of contact separation to sweep the arc quickly from the contacts, thereby permitting both main and arcing contacts to remain in the chute; (2) the ability to increase the cross-sectional area of the main current-carrying member within wide limits, without affecting any of the parts

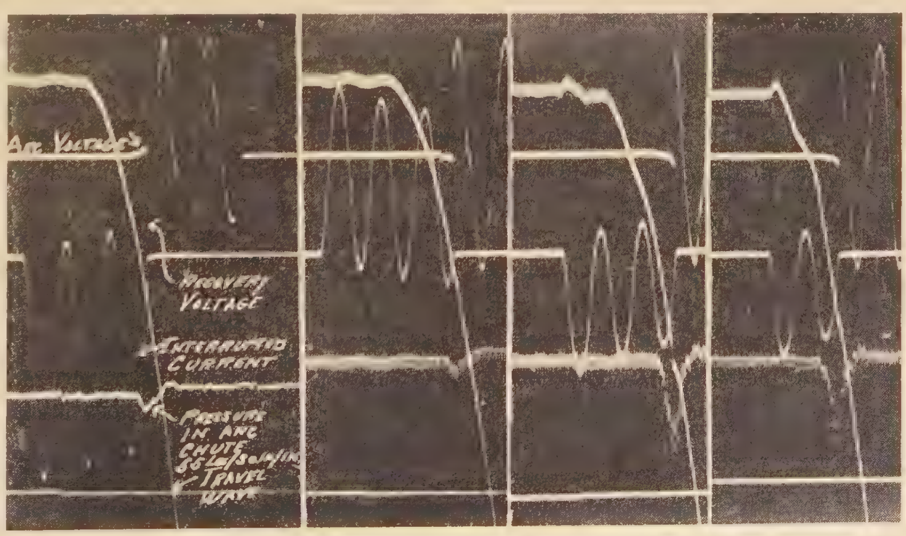
Figure 7. Magnetic oscillograms from table III

Fault current (amperes)—from left to right:

6,200 15,800 29,000 40,000

Recovery voltage (kv)—from left to right:

13.1 12.7 12.4 12.6



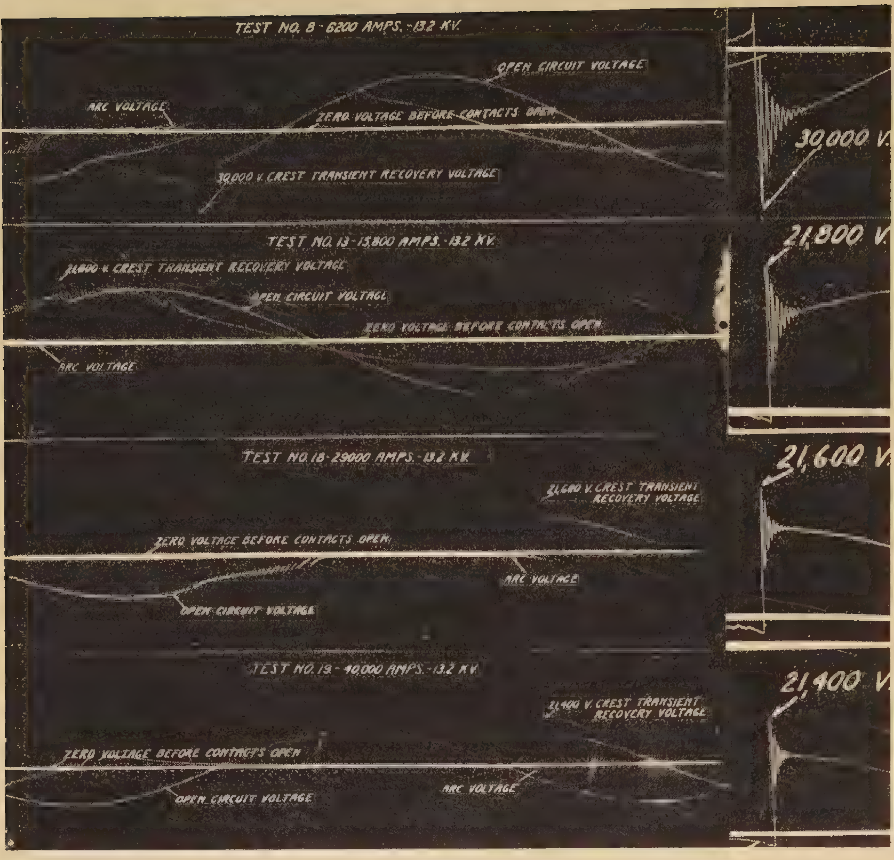


Figure 8. Cathode-ray oscillograms corresponding to those of figure 7

involved in arc extinction. These two factors simplify the construction of the breaker and are of particular importance on the heavier current units of the power-house class.

An experimental arc chute as shown in figure 3 was built along these lines for test. This form of interrupter is flexible and can be adapted to a breaker design as shown in figure 4, or it can be disposed horizontally, depending on the application requirements. Figure 5 shows an open view of this same chute after having successfully interrupted 45 short circuits at currents varying from 1,000 to 50,000 amperes at 13,200 volts as listed in table III. During the tests the interrupter was in a horizontal position on the breaker. After these tests the contacts were found to be in excellent condition. There was some erosion of the splitters as may be seen, however, this erosion was not sufficient to render them unfit for further service.

Referring to figure 5, (1) is the stationary contact from which the moving contact (2) is withdrawn pulling an arc along the path (3). This arc under the action of a blast of air from the orifice (4) is driven into intimate contact with the splitters (5) along the path (6). The arc gases expelled from the throat impinge first on the copper buffer plates (7) which perform the first cooling and deionizing action on the arc gases. The partially cooled and deionized gases then pass on through the cooling and diffusing screens (8) that cool and diffuse the arc gases effectively preventing external flame and disturbance.

Test Results

Tables I, II, and III show the results of three typical series of single-phase tests using the arc chute shown in figure 3. During these tests the pressure in the tank varied between 105 and 150 pounds per square inch. The pressure in the arc chute was measured with an instantaneous recording telemeter. This pressure was negligible except during the arcing period. The effect of the arc acting as an impediment to the free escape of air caused a temporary build-up in pressure back of the arc which in some cases almost equalled the tank pressure.

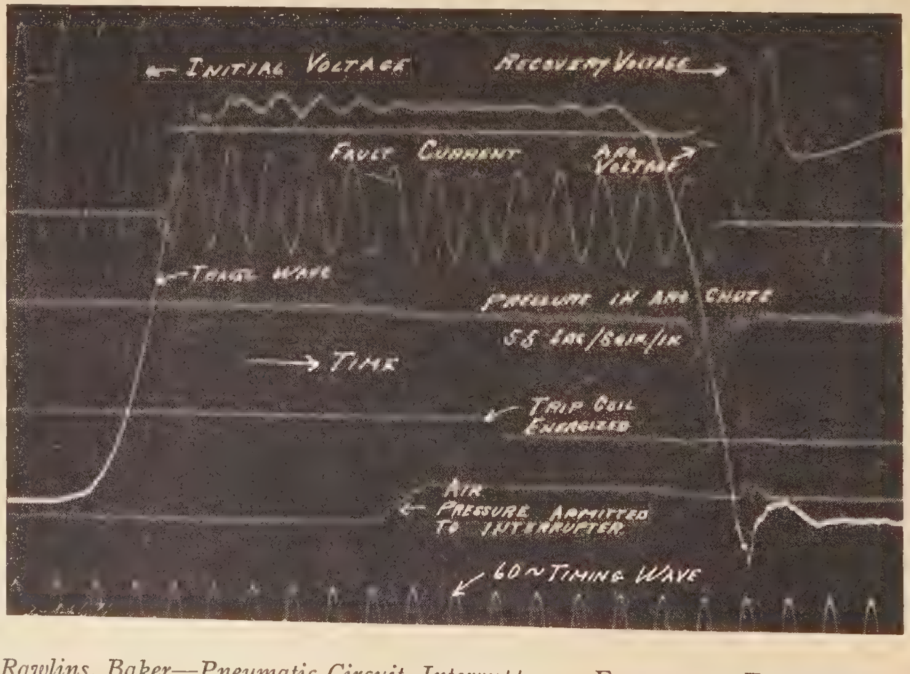
The arcing time was generally less than that corresponding to one-half cycle of current. Sometimes when the current was highly asymmetrical arcing would continue over one entire current loop which would lengthen the time to over one-half cycle. The breaker rarely passed up an opportunity to clear if the contacts were parted one-half inch or more when a current zero occurred.

Tables I and II show currents ranging from approximately 1,000 amperes to 52,000 amperes with 13.2 kv across a single-pole unit.

Figure 6 shows typical oscillograms taken from table I at 1,000, 12,700, 35,000, 48,000, and 53,000 respectively. The oscillograms from table II are all very similar to the ones shown in figure 6.

Table III shows a series of 45 tests covering the same current range. On some of these tests cathode-ray oscillograms were obtained, these together with the magnetic oscillograms shown in figures 7 and 8 are of interest in proving that the operation of the breaker is consistently fast and dependable even on a circuit with a natural oscillatory frequency of 28,300

Figure 9. Typical oscillogram of closing-opening tests



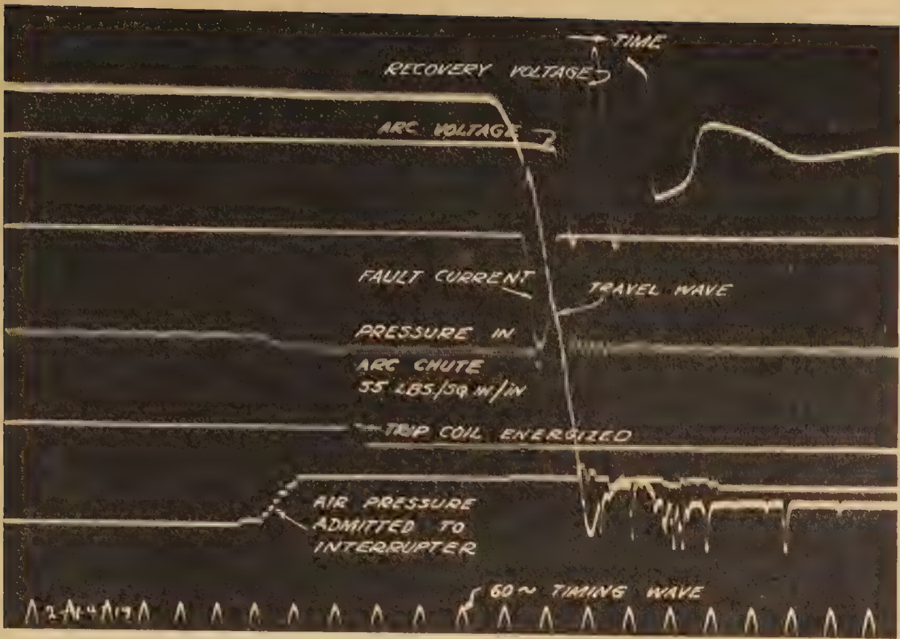


Figure 10. Oscillogram showing interruption of 65,300 rms amperes at 13.2 kv, single phase

cycles per second, and a circuit transient recovery voltage rate of 2,200 volts per microsecond. On this circuit the test transient recovery voltage rate was 1,380 volts per microsecond as shown for test 19. The transient recovery voltage rate is given as the slope of the tangent to the recovery voltage wave. It is obtained by dividing the maximum voltage by the time of one-half cycle of natural frequency and multiplying by 1.15. This method is used because the recovery transient consists essentially of a single sinusoidal component.

Figure 9 shows a typical closing-opening test. The ability of this breaker to close in on high current without showing any evidence of distress is noteworthy.

Figure 10 shows an oscillogram of the highest current interrupted. It was obtained during a fourth run similar to the one shown in the tables. This film shows satisfactory interruption of 65,300 amperes rms at 13.2 kv, single phase.

These interruptions were obtained with negligible external demonstration in the form of ionized flame. Noise accompanying the interruption is held to acceptable limits by the arc chamber design as shown. A particularly significant feature of all tests is the high mechanical speed of the breaker contacts. It is possible to separate these contacts two inches in one-half cycle. This high speed is the effect of properly using an air mechanism to operate the breaker. Very high opening and closing forces can be exerted on the piston which is moved in the cylinder by the compressed air itself to actuate the contacts. Springs which would give comparable operating speeds would represent a nearly impossible mechanical design. It is also a simple matter properly to control the air cylinders to stop the contacts and their associated operating rods without undue jar on rebound at the end of the opening stroke.

A compressed-air interrupter of the type described appears to be particularly rugged and to handle repeatedly interruption of the highest currents without excessive damage. The low energy input into an interrupting chamber of this type which is the function of careful design to minimize the arcing time, to approximately one-half cycle, and to keep the arc drop low during the arcing period, is primarily responsible for reliability without excessive erosion.

Table IV. Summary of Information From Cathode-Ray Oscillograms

Test Number	Frequency (Cycles/Sec)	Crest Voltage	Test Transient Recovery Voltage Rate (Volts/Microsec)	Circuit Transient Recovery Voltage Rate (Volts/Microsec)
*8	13,500	30,000	920	1,050
*13	23,500	21,800	1,150	1,820
*18	24,400	21,600	1,210	1,890
*19	28,300	21,400	1,380	2,200

* Magnetic oscillograms and cathode-ray oscillograms of these tests are shown in figures 7 and 8 respectively.

Conclusions

The search for improved forms of dry-type circuit interrupters suitable for interruption of 1,500,000 kva, at 15,000 volts, indicates that the use of a compressed-air stream transverse to an arc is the most effective. Currents as high as 65,300 amperes have been interrupted at 13,200 volts single phase with a contact separation of approximately two inches, which can be mechanically obtained in one-half cycle. A breaker utilizing these new principles of interruption makes possible new standards of system protection because of its high operating speed, complete freedom from oil and associated fire hazard, and remarkably high interrupting capacity in terms of the space required by the breaker.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

What Wood May Add to Primary Insulation for Withstanding Lightning

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ON power-transmission lines, wood, serving certain structural functions, simultaneously may provide supplementary insulation against lightning if properly chosen and applied. However, to sustain the power-frequency voltage, adequate primary insulation in the form of porcelain insulators or the like is essential.

These facts have been rather well known for some time, but in degree the ability of wood to withstand lightning has not been thoroughly determined. In the laboratory study described two years ago,[1] this phase was partially covered. It is the purpose of this paper to describe the results of a testing program in the same laboratory, treating of all factors which it was felt could affect the lightning or impulse strength of wood.

Nothing relating to the 60-cycle strength of wood will be given here, for, as outdoor insulation against sustained power-frequency voltage, wood, with its internal moisture, is generally considered quite ineffective. For briefly applied surges, such as lightning or switching transients below flashover voltage, the moisture content is not damaging to the wood. However, for sustained 60-cycle voltages, the electrolytic nature of the moisture allows leakage currents which ultimately cause burning and charring of the wood. As intimated above, it is the purpose of effective primary insulation in series with the wood to check this action.

It will be shown below that the degree to which wood will supplement porcelain against lightning depends almost entirely upon its length and internal moisture, and little upon its creosoting treatment, cross section, or kind. Considerable test data were obtained in this study and numerous curves and tables developed directly therefrom. In the interest of brevity and clarity, practically all of these original curves are omitted here and only so-called "working curves" which were derived from the originals, are included. Accordingly, most of the kilovolts of insulation plotted involve actual supplementary wood insulation values to be added directly to the impulse kilovolts of the associated insulators. Likewise, ratios and percentages are used for expressing the effects of certain wood properties upon the insulation strength of wood.

Nature of Test Equipment and Data

The various stages of the 3,000,000-volt impulse generator at the Barberton high-voltage laboratory of the Ohio Brass Company were used in these tests. The generator itself was always adjusted for the standard $1^1/_2$x40-microsecond wave.

For tests on the wood specimens alone, voltage was applied between braided metallic bands tightly wrapped about the wood. This was felt to simulate electrically most hardware conditions in service. In the case of a combined insulator and wood test, voltage was applied to the conductor attached to the insulator while the braided band was adjusted along the wood member and grounded. For all tests, the specimens themselves were suspended at sufficient distances from nearby grounded objects to eliminate interference with the electrostatic fields being studied.

On practically all specimens, complete volt-time curves were taken with both positive and negative polarities, cathode-ray oscillograms being secured for every impulse. To allow compactness of presentation, however, curves are given showing flashover voltages at only the two-microsecond and "critical" (formerly termed "50-50" or "minimum") points. It is felt that the two-microsecond point represents direct-stroke conditions of average severity while the critical flashover values allow computations for induced voltages and other long-wave conditions.

Flashover Voltages of Structure Parts

As pointed out above, any structure design computations made from information in this paper require the addition of the supplementary wood values from certain curves to actual insulator flashover values. Figures 1 and 2 provide the necessary flashover data of a pin-type and a suspension insulator for use in typical examples in this paper.

Figure 3 affords rod-gap data for assisting in designing so-called "horn gaps" for wood members. As will be shown by later examples, such gaps can be made to protect parallel crossarm or pole paths if adjusted to have lower flashover strengths. The proper crossarm and pole data for this comparative study is provided in the curves of figures 4 and 5. No measurable difference was found for surges of the two polarities so that the curves of these two figures represent the average of all data. The data from figures 4 and 5 are only for comparison with other parallel flashover paths, such as air gaps or insulators, and they are not to be added to other insulation in series.

Flashover Voltages Added to Porcelain by Wood

In figures 6 to 9 are given the supplementary impulse insulation strengths afforded porcelain insulators by different lengths of various wood members. For each case the flashover data from the curve *must be added* to the corresponding flashover data of the insulator chosen in order to have the total lightning or impulse strength of the combination. The supplementary insulation values which

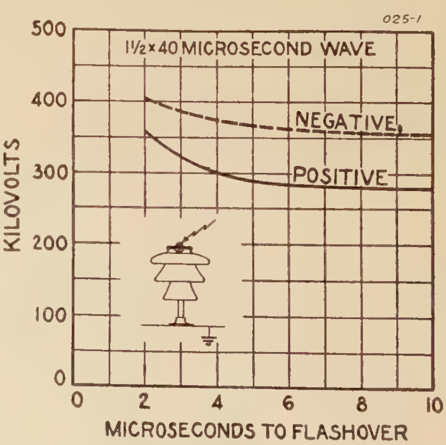

Figure 1. Impulse volt-time curve of 69-kv pin-type insulator

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Crossarm and pole specimens used in many of the tests were from the Georgia Power Company, Mississippi Power Company, New England Power Service Corporation, and Ohio Power Company. The special creosoted planks with known moisture contents were prepared by the Wood Preserving Corporation under the direction of W. P. Arnold.

1. For numbered reference, see end of paper.

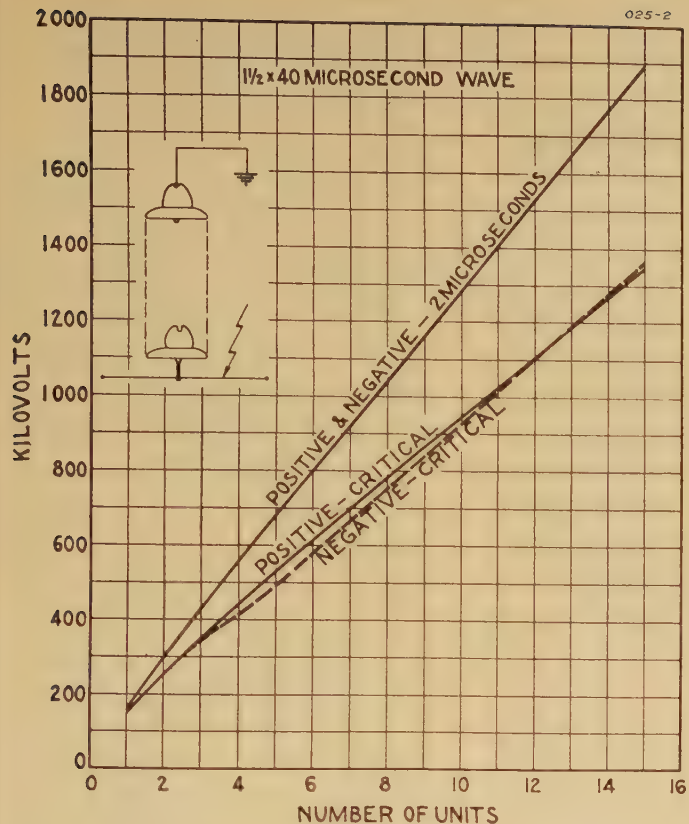


Figure 2. Impulse flashover voltages of 10 by $5^3/_4$-inch suspension insulators

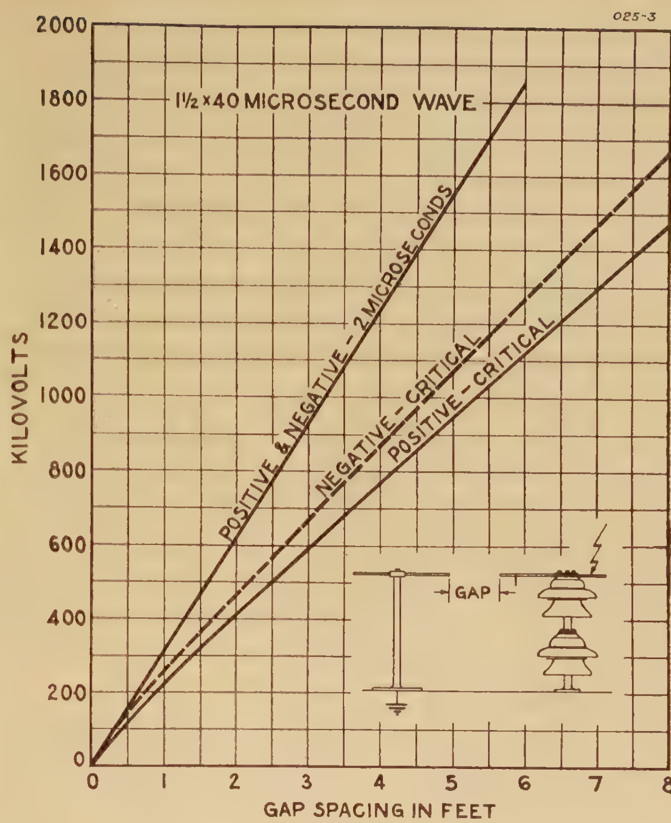


Figure 3. Impulse flashover voltages of rod gaps

pole sections add to pin-type crossarm combinations (figure 6) are shown in figure 10.

All wood insulation values in figures 4 to 10 inclusive, except for cedar and newly creosoted pine poles in figure 5, are based on tests on wood with an average moisture content of about 15 per cent.

Data, described in the paper referred to above,[1] indicated that the total insulation strengths of insulator and wood combinations could be calculated by multiplying the sum of the individual flashover strengths by certain constants. Subsequent and more numerous data, however, tend to prove that more accurate calculations can be made by the use of curves such as given in figures 6 to 10. Also, an analysis of the electrostatic conditions involved tends to bear this out. For example, the effect of changing the constants of one member, such as by lengthening indefinitely the crossarm supporting the insulator, cannot always allow the actual flashover voltage to be the same percentage of the sum of the insulator and arm flashover voltages.

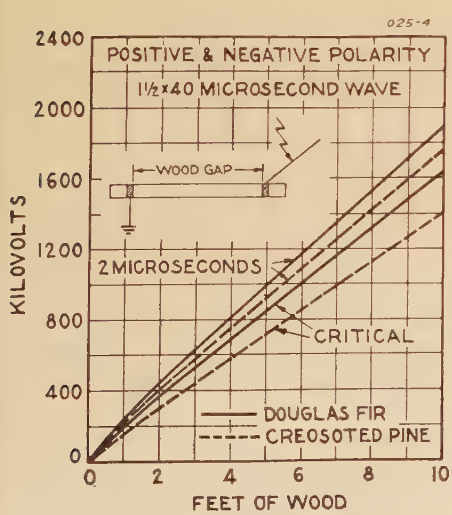


Figure 4. Impulse flashover voltages of wood crossarms

Factors Influencing Impulse Insulation Values

Cross Section

Previously published data[1] indicated that the impulse flashover voltage of wood decreases as its cross-sectional area is increased. This subsequent investigation, however, shows that certain other factors have greater effects and that cross-sectional area is of secondary importance.

Another related factor which may affect the flashover voltage is the distribution of the wood cross section, as exemplified by solid and multiple-plank crossarms with equal cross-sectional areas. The ratios in figure 11 are the result of flashover tests upon a number of combinations of insulators and creosoted pine timbers. The latter were first tested as six by eight-inch solid crossarms and then sawed and retested as three by eight-inch double plank crossarms. The average ratio for the positive critical flashover is about 0.96 and that for the negative is about 1.02, indicating that as far as the impulse flashover voltage is concerned, there is little to be gained by the choice of one type of construction over the other. However, a definite advantage is gained with the double-plank crossarm in that a lightning stroke damages only one member and leaves the other intact for supporting the line.

Creosote Treatment

Since wood used in power-line structures may be creosoted, it is desirable to know the effects on flashover voltages of the various kinds of creosote, degrees of retention, and methods of treatment. A number of flashover tests were made on three-foot sections of newly creosoted green pine crossarms in series with three 10 by $5^3/_4$-inch suspension insulators. Light creosote with retentions of eight and ten pounds per cubic foot of wood, and heavy creosote with a ten-pound retention were used in the preparation of the test specimens. Results of these tests, some of which are shown in figure 12, indicate

that no appreciable difference is caused by the various grades of creosote or retentions. Still other tests indicate that the flashover voltage of wood is about the same when treated by different commercial creosoting processes.

In order to study the relative flashover voltages of creosoted and untreated wood, several pairs of specially prepared dry pine timbers were tested. Each pair was obtained from the same original plank, and only one of each pair was creosoted. The results, shown in figure 13, indicate that creosoting reduces the flashover voltage of the combination of wood and suspension insulators only 6 or 7 per cent.

Pine used in power-line structures is usually creosoted while Douglas fir may be used either untreated or creosoted. Various tests show that there is no appreciable difference between the flashover voltages of untreated and creosoted Douglas fir, either by itself or in combination with insulators. Accordingly, all of the flashover curves from figures 4 to 10 inclusive which include Douglas fir may be used for both creosoted and untreated wood.

Rain

Since lightning is usually accompanied by rain, it seemed desirable to know the effects of rain on the impulse insulation of wood. It had been reported previously[1] that rain may reduce the impulse flashover of wood structures by as much as 50 per cent.

In order to determine whether such a reduction is caused by rain in the air, and on the insulator and wood surfaces, or by the moisture penetration into the wood, a special series of tests was made. A dry Douglas-fir crossarm was completely covered with several coats of lacquer to keep out moisture and subjected to dry and wet flashover tests. The wet tests were made using standard AIEE rain (precipitation 0.2 inch per minute; resistivity, 7,000 ohms per inch cube). Similar tests were made upon unlacquered Douglas fir, red elm, and red oak, these woods being chosen because of their dense structure. The results of these tests are presented in figure 14 as the ratio of wet to dry flashover voltage.

As shown, the critical flashover voltages of the unlacquered woods are reduced on the average to about 65 or 70 per cent of the dry flashover values, and the two-microsecond to about 75 or 80 per cent. Those of the lacquered crossarms showed a change of less than 10 per cent. The ratios exceeding unity for the lacquered arm are probably the result of the increased dielectric strength of air under rain conditions. Since the flashover value of each unlacquered crossarm was reduced considerably by the rain while that of the lacquered arm was practically unchanged, it seems logical to presume that the penetration of moisture into the wood is the fundamental cause of the observed reduction.

The effect which the duration of rain has upon the impulse insulation of wood and insulators is indicated in figure 15. The tests here were made on four-unit insulator strings suspended from four-foot sections of both untreated Douglas-fir and creosoted-pine crossarms. The greatest reduction in flashover voltage seems to occur within a very few minutes after the rain starts, negligible change resulting thereafter.

While rain definitely reduces the impulse insulation of wood structures, there is always a chance that the wood may not be wet at the instant it is subjected to a lightning voltage. Furthermore, the standard rate of precipitation used in these tests far exceeds the usual rate of natural storms. Accordingly, it is possible that the flashover voltage may not decrease as rapidly as indicated in figure 15. In general, therefore, the actual reduction factor for rain for a given condition appears to be a matter of probability.

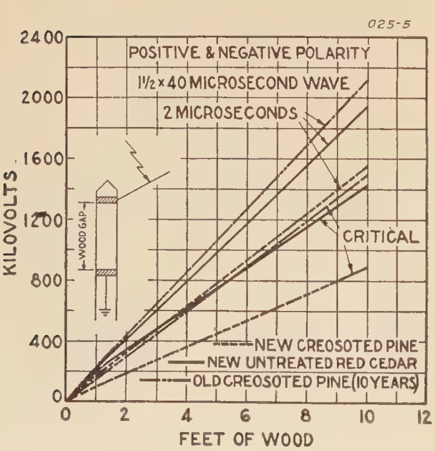


Figure 5. Impulse flashover voltages of wood poles

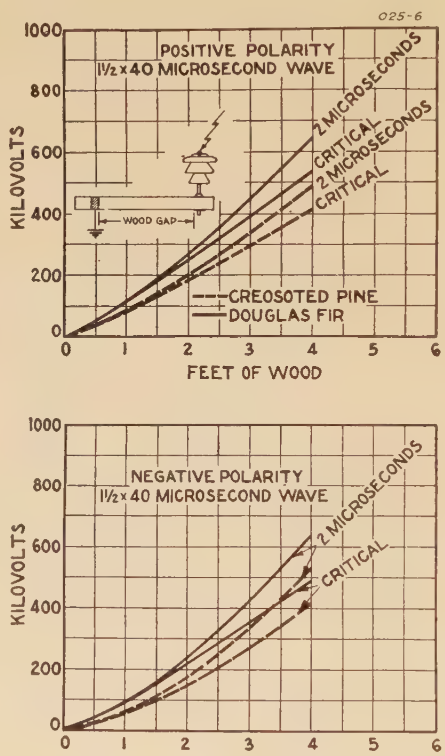


Figure 6. Impulse insulation added to pin-type insulators by crossarms

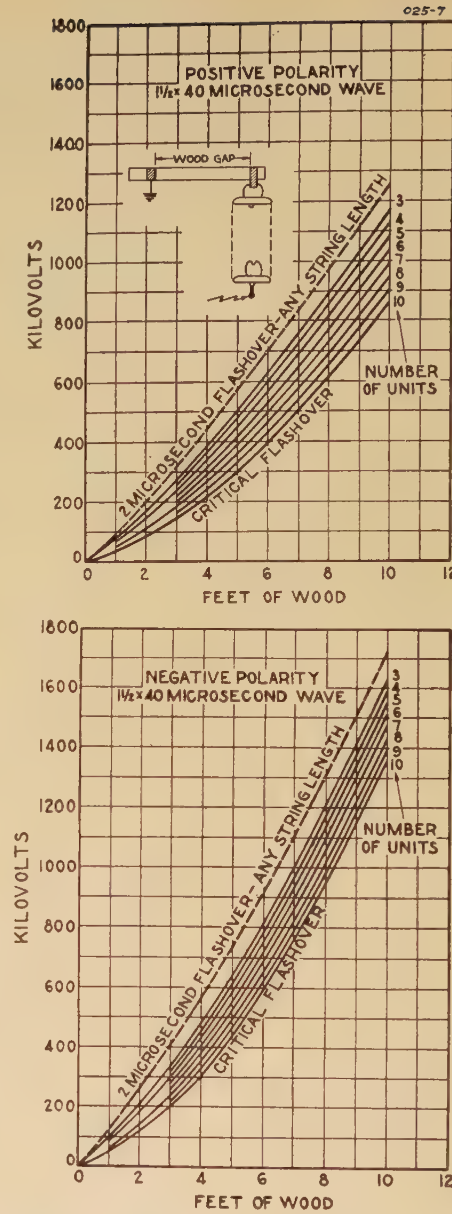


Figure 7. Impulse insulation added to suspension-insulator strings by wood crossarms (creosoted pine or Douglas fir)

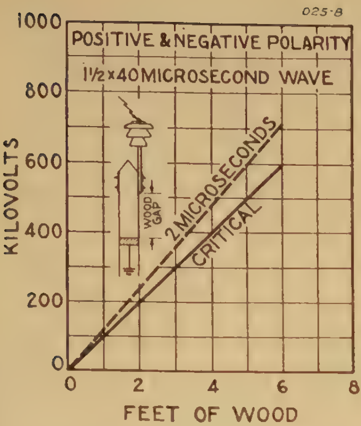


Figure 8. Impulse insulation added to pin-type insulator by pole sections (creosoted pine)

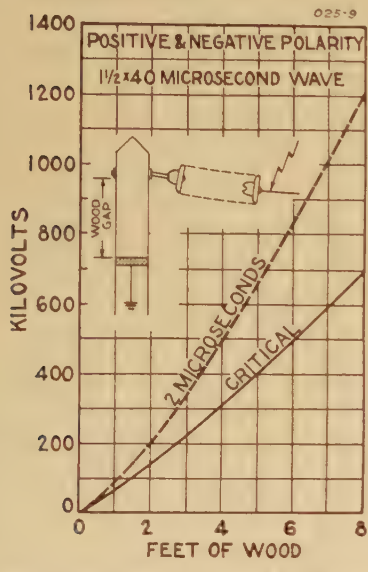


Figure 9. Impulse insulation added to suspension-insulator strings by pole sections (creosoted pine)

Moisture Content

The results of the various rain tests indicated that moisture penetration into the wood was responsible for the reduction of its impulse flashover voltage. Furthermore, it had been observed that green wood has a lower flashover voltage than equivalent dry wood. Accordingly, it seemed desirable to conduct a systematic investigation of the effects of internal moisture upon the impulse flashover voltage of wood.

Figure 16 gives results of flashover tests on four-unit strings of 10 by $5^3/_4$-inch insulators suspended from four-foot sections of creosoted-pine crossarms with moisture contents varying from 12 to 93 per cent. Similar tests were made on the same crossarms without insulators. Other tests were also made on similar arrangements of untreated Douglas-fir crossarms with controlled moisture contents.

The results of this study are presented in figure 17 as the ratio of the flashover voltage at any moisture content to the flashover voltage at 15 per cent moisture content. The latter is usually considered the average for dry wood in moisture equilibrium with the atmosphere.

When wood with internal moisture is placed under electrical stress, electrolytic conduction may occur within it. This might influence the electrostatic field of the wood, and therefore, its flashover voltage in combinations with insulators. The degree to which this would take place may vary with the different woods because of their internal cellular structures. This may account for the difference in behavior of the several woods in the curves of this paper. The amount of voltage reduction introduced by internal moisture also may be dependent upon the duration of the transient, as

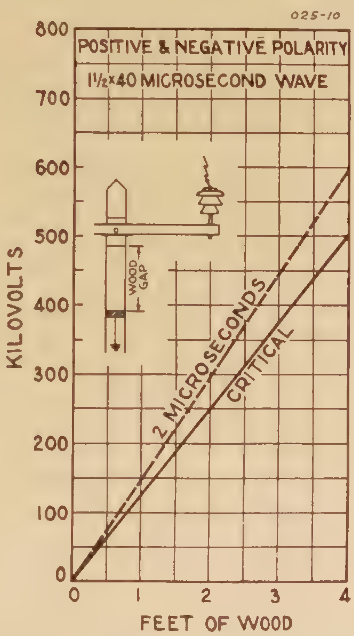


Figure 10. Impulse insulation added to combinations of pin type with crossarm by sections of poles (creosoted pine)

time is required for electrolytic conduction. This may be a possible explanation of why the two-microsecond flashover voltage (figure 17) is influenced less than the critical by the internal moisture.

From figure 5, the critical flashover voltage of eight-foot sections of newly creosoted pine poles is about 720 kv while that of old poles is about 1,200 kv. The ratio of these flashover voltages is about 0.60, which corresponds to a moisture content of about 33 per cent on the creosoted pine curve in figure 17. The newly creosoted pine poles were presumably green wood while the old poles were fairly dry, having been in service for several years. A moisture content of 33 per cent is a reasonable value for green wood and, accordingly, it would seem that the curves shown for crossarms (figure 17) may be satisfactory for poles as well.

As shown by the curves of figure 17, an immediate increase of impulse insulation strength may be secured by predrying wood to its equilibrium value before it is installed on transmission-line structures. On the other hand, the insulation value of green wood will increase gradually to the same level as its internal moisture approaches equilibrium with that of the atmosphere. Accordingly, the choice between predried and green wood appears to be a matter of economics.

Spread of Data

All curves presented in figures 4 to 10 inclusive represent the average of numerous data points, which lie within ±15 to ±20 per cent of the average. These rather wide limits are believed to be the result of inherent structural variations within the wood itself which influence its impulse flashover voltage.

Critical flashover tests were made on a group of about 60 newly creosoted pine poles, each pole being subjected to the same test procedure. These flashover voltages ranged from 490 kv to 836 kv, averaging about 675 kv. The spread of data with respect to the average was as follows:

Spread of Data in Per Cent	Number of Test Values Included	Per Cent of Total Number of Test Values Included
± 5	25	41
±10	41	67
±15	48	79
±20	56	92
±25	60	98
±28	61	100

In the above table 92 per cent of all

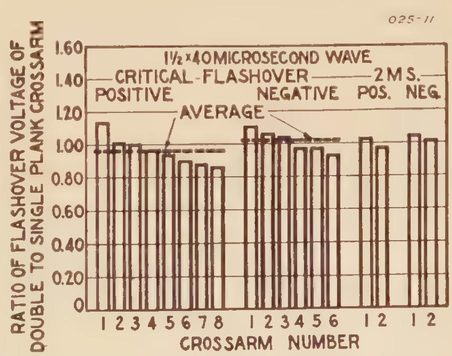


Figure 11. Comparison of impulse flashover voltages of single- and double-plank crossarms with pin-type and suspension insulators

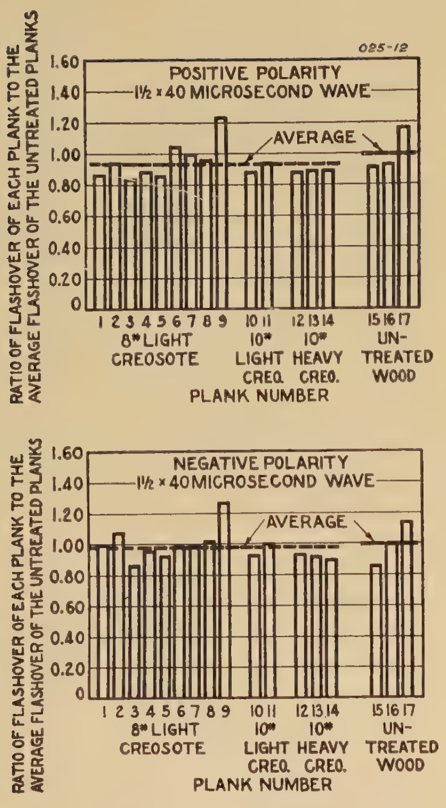


Figure 12. Effects of various creosotes and retentions upon impulse flashover voltages of pine crossarms with suspension-insulator strings

Table I. Protective Horn Gaps on Creosoted Pine Crossarms for Six Feet of Green Wood

	Positive		Negative	
	Critical	Two-Micro-second	Critical	Two-Micro-second
Flashover of dry wood (figure 4) in kv	840	1,080	840	1,080
Assumed moisture content in per cent	35	35	35	35
Reduction factor (figure 17)	0.57	0.77	0.57	0.77
Flashover of green wood in kv	480	830	480	830
Rod gap having flashover equal to that of green wood (figure 3) in inches	0.29	832	25	32

the tests are included in a ±20 per cent spread while a ±25 per cent spread includes all but one test. Similar distributions of test values would probably be found for various combinations of insulators and wood, although the spread in the above tabulation of green-pole data is probably as great as would ever be found.

When the curves of figures 4 to 10 inclusive are used for estimating the flashover voltage of a given structure, the result obtained will represent the average flashover voltage of a large number of similar structures. For example, if tests were made on 100 similar structures the average of these test values would probably agree quite closely with the estimated average and 90 to 95 per cent of these tests would lie within a ±20 per cent band.

Application of Curves to Typical Problems

General Procedure

By means of the curves in this paper it is possible to estimate the various impulse flashover voltages of numerous combinations of insulators and wood.

The first step is to obtain the flashover voltage of the insulator, either from figures 1 or 2 or from other reliable sources. The second step is to determine from the proper curve the kilovolts of insulation *added* by the wood and *add* it to the flashover voltage of the insulator. The result will be the average flashover voltage of the given combination of insulator and wood with a moisture content of about 15 per cent. If the wood is green, this flashover voltage should be multiplied by the proper reduction factor, selected from the curves of figure 17 for the known moisture content of the wood. The moisture content of creosoted green pine may vary from 30 to 60 per cent, and in cases where the actual moisture content is unknown, an average value of 35 per cent would probably give satisfactory results. Green fir and cedar can be expected to be no higher than 35 per cent in moisture content. Incidentally, this may account for the flashover voltage curve of new cedar poles in figure 5 being higher than that of new creosoted pine poles.

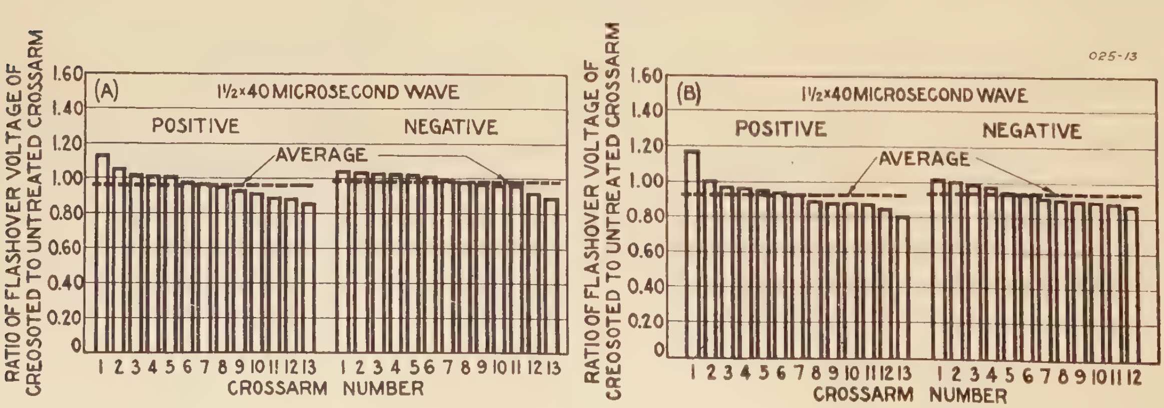
In case the flashover voltage under rain conditions is desired, the flashover voltage, estimated for the combination of insulator and dry wood, should be multiplied by the proper reduction factor. From the results presented in figures 14 and 15, it would appear that a factor of 0.65 to 0.70 for critical flashovers and 0.75 to 0.80 for two-microsecond flashovers of either polarity would be suitable reduction factors due to the rain.

Tests previously discussed have indicated that the reduction in impulse flashover voltage caused by rain is due primarily to moisture penetration into the wood and not to a reduction in the impulse flashover voltage of the insulators or the surrounding air. Therefore, it seems a reasonable presumption that the impulse flashover voltage of a green crossarm with a high moisture content should not be lowered appreciably by rain. Accordingly, both a moisture-content reduction factor and a rain reduction factor should not be applied to the estimated flashover voltage for dry wood. The factor giving the lower flashover voltage would be the proper one to use in estimating the flashover voltage under adverse conditions.

Examples

The following examples are presented to illustrate several applications of the curves in this paper and to demonstrate the agreement of estimated with actual test values.

Figure 13. Effect of creosote treatment of wood upon its impulse flashover voltage with and without insulators



(*A*)—Five feet of creosoted pine crossarm only

(*B*)—Five feet of creosoted pine crossarm with five 10 by 5³/₄-inch suspension insulators

Example 1. In this example the dry and wet impulse flashover voltages of a 69-kv pin-type insulator and four feet of creosoted pine crossarm are determined.

Positive Critical		
Flashover of insulator (figure 1)		260 kv
Insulation added by wood (figure 6)		410 kv
Estimated flashover, dry		670 kv
Actual test value, dry		690 kv
Ratio of estimated to actual	0.99	
Reduction factor due to rain	0.65	
Estimated flashover, wet		435 kv
Actual test value, wet		445 kv
Ratio of estimated to actual	0.98	

The negative critical, and positive and negative two-microsecond flashover voltages may be estimated in a similar manner.

Example 2. In this example the estimated voltage is for phase-to-phase flashover between conductors supported by two 33-kv pin-type insulators on the same 22-inch creosoted pine crossarm with two wood sections between phases such as results from the use of metal crossarm braces. When an impulse is applied between conductors, each combination of insulator and wood section is subjected to an impulse of opposite polarity from the other. Accordingly, the procedure is to estimate the positive and negative critical flashover voltages for one insulator and wood section, add these two estimates together, and multiply by a factor of 0.85. The latter is chosen because tests have indicated that when two such combinations are placed in series the resulting flashover voltage averages about 0.85 of the sum of the flashover voltages of the individual combinations. Similarly, a factor of 1.00 has been determined for the two-microsecond flashover. There is evidence that the same procedure will prove satisfactory for strings of suspension insulators in place of pin type.

Critical Flashover		
Positive critical flashover of pin type	200 kv	
Insulation added by wood (figure 6)	165 kv	
Total, positive		365 kv
Negative critical flashover of pin type	255 kv	
Insulation added by wood (figure 6)	130 kv	
Total, negative		385 kv
Sum, positive and negative		750 kv
Reduction factor	0.85	
Estimated flashover, positive or negative	640 kv	
Actual test value, positive	620 kv	
Ratio of estimated to actual, positive	1.03	
Actual test value, negative	650 kv	
Ratio of estimated to actual, negative	0.98	

The method of estimating used in this example naturally gives the same value for both polarities and actual tests indicate that there is little difference between the positive and negative flashover voltages of this combination of wood and insulators.

Example 3. In order to avoid shattering of crossarms when struck by lightning, parallel horn gaps are sometimes used which have shorter spacings than the sections of wood being protected. The intention is to have the flashover voltage of the horn gap somewhat lower than that of the wood in parallel with it, so that flashover will occur over the gap and not along or in the wood.

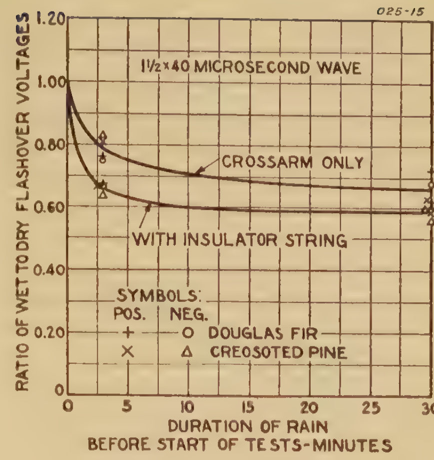


Figure 15. Effect of standard AIEE rain duration on critical impulse flashover voltage of suspension-insulator string and wood crossarm

Using the rod gap curves of figure 3 and the crossarm curves of figure 4, it is possible to estimate horn-gap spacings which will protect wood. Table I illustrates how such an estimate is made.

To protect the crossarm, it is evident that a 25-inch gap would be the longest permissible. In a series of tests run on six-foot sections of four creosoted pine crossarms, the protective gaps were found to be 24, 24, 25, and 27 inches, which are in good agreement with the above estimates.

Example 4. Horn gaps are occasionally used on poles in series with the down-lead to increase the impulse insulation of the pole top with respect to ground. A single pole gap with a 30-inch spacing is oc-

A—Douglas fir, lacquered, test 1
B—Douglas fir, lacquered, test 2
C—Red elm, untreated, test 1
D—Red elm, untreated, test 2
E—Red oak, untreated, test 1
F—Red oak, untreated, test 2
G—Douglas fir, untreated, test 1

Test 1—Four feet of wood plus a four-unit string of 10 by $5^3/_4$-inch suspension insulators

Test 2—Four feet of wood plus one 69-kv pin-type insulator

Figure 14. Effects of rain upon impulse flashover voltages of combinations of wood and insulators

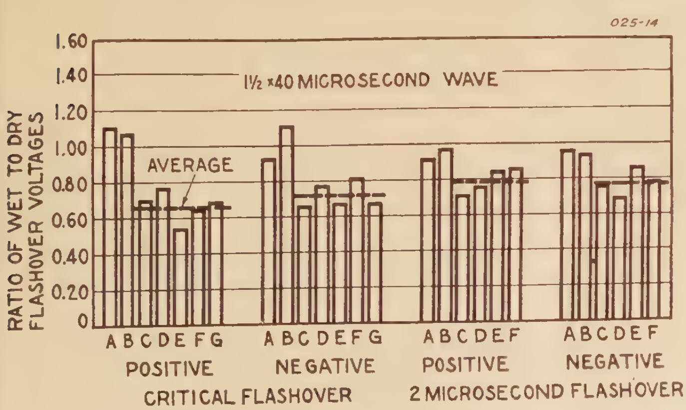
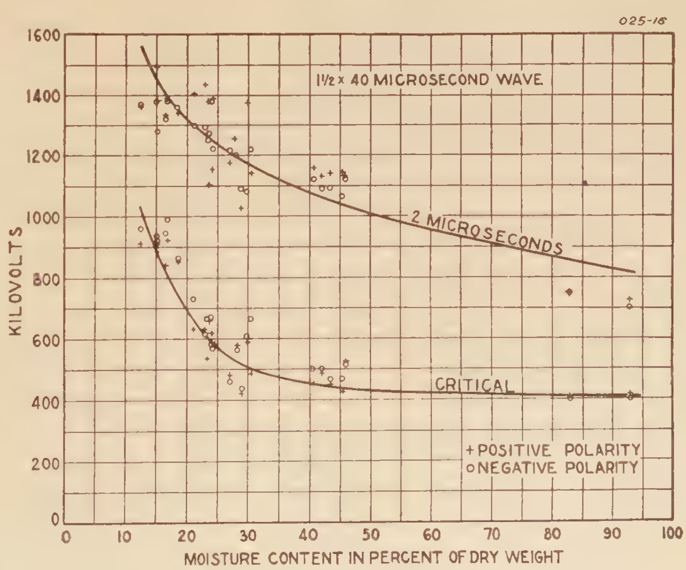


Figure 16. Effects of moisture contents of wood upon impulse flashover voltages of wood crossarms with suspension-insulator strings



casionally used in parallel with about 94 inches of wood. The example in table II shows that such a gap adequately protects the wood, even if it is newly creosoted pine.

The excellent agreement between the actual test values and the flashover voltage of the equivalent rod gap indicates that rod gap curves may be used for estimating horn-gap flashover voltages with a fair degree of accuracy.

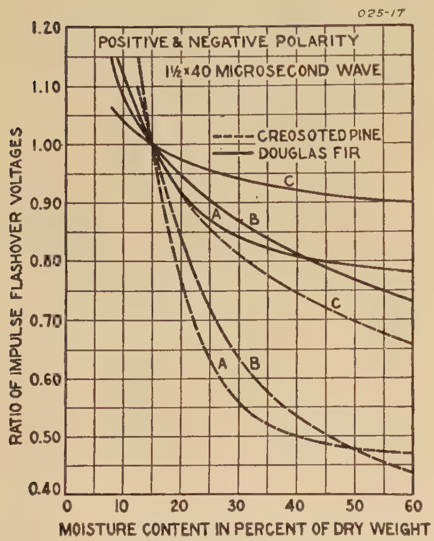


Figure 17. Ratio of impulse flashover voltages for various moisture contents relative to 15 per cent moisture

A—Critical flashovers, crossarms with suspension insulator strings

B—Critical flashovers, crossarms alone

C—Two-microsecond flashovers, crossarms alone or crossarms with suspension insulator strings

Example 5. In H-frame wood structures it is sometimes desirable to have the flashover voltage of the insulator string and crossarm somewhat greater than that of the horizontal air gap between line conductor and down-lead on the pole to protect the crossarm from shattering. In this example, the number of suspension insulators necessary to force the flashover to occur on the horizontal gap is determined (table III).

Table II. Thirty-Inch Protective Pole Gaps on 94 Inches of Newly Creosoted Green-Pine Poles

	Positive		Negative	
	Critical	Two-Microsecond	Critical	Two-Microsecond
Flashover of 94 inches of pole (figure 5) in kv	700	1,200	700	1,200
Flashover of 30-inch rod gap (figure 3) in kv	500	770	570	770
Actual test value in kv	485		570	

Table III. Required Number of Suspension Insulators on Six Feet of Creosoted Pine Crossarm to Force Flashover on Six-Foot Air Gap to Down-Lead

	Positive		Negative	
	Critical	Two-Microsecond	Critical	Two-Microsecond
Flashover of six-foot rod gap (figure 3) in kv	1,120	1,850	1,270	1,850
Flashover of crossarm with the following number of suspension insulators (figures 2 and 7) in kv:				
6 insulators	1,130	1,510	1,300	1,720
7 insulators	1,190	1,630	1,350	1,840
8 insulators	1,230	1,750	1,410	1,960
9 insulators	1,280	1,870	1,460	2,080
10 insulators	1,340	1,990	1,520	2,200

From table III, it is evident that the nine-unit insulator string is the shortest causing flashover voltages higher than all corresponding voltages of the rod gap. Accordingly, it should be expected to give the desired crossarm protection. In a series of actual tests on creosoted pine crossarms, a ten-unit string was required to cause flashover along the desired path.

Conclusions

1. Properly selected and controlled wood may add appreciably to the lightning insulation of a line. The magnitude is more or less in proportion to the wood length and may be estimated from curves presented in this paper.

2. Almost without exception, the lower the moisture content of wood the higher will be its supplementary lightning insulation value; in particular, reducing the moisture content from an average green-wood value of about 35 per cent to an average moisture equilibrium value of about 15 per cent may nearly double the insulation strength of creosoted pine structures, and raise that of fir structures by about one-fourth. The increase for various moisture contents may be estimated from figure 17.

3. During a rain storm, the lightning insulation strength of structures utilizing wood as supplementary insulation may suffer reductions to as low as 65 per cent of the dry flashover voltage within two or three minutes after the start of rainfall; further reduction, with continuation of the rain, is inappreciable.

4. The supplementary lightning insulation strength of wood is not appreciably altered by the grade of creosote, degree of retention, or creosoting process used in its treatment.

Reference

1. Lightning Strength of Wood in Power Transmission Structures, Philip Sporn and J. T. Lusignan, Jr. AIEE Transactions, volume 57, 1938, pages 91–101.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Analysis of Bushing-Current-Transformer Performance

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Synopsis: This paper is a presentation and discussion of the more important results obtained in a series of extensive tests made on bushing current transformers. In addition to the determination of the ratio and phase-angle characteristics, tests were made to determine the division of current in interconnected secondary circuits for conditions simulating actual faults in the primary circuit. It is also shown that most of the results obtained from the tests may be readily calculated from the excitation-current data.

IN the application of protective relays for transmission and high-voltage distribution substations, it is vitally important to give careful consideration to the ratio and phase-angle characteristics of the bushing current transformers used as accessory equipment. This has long been recognized, but the necessity for a wider scope of understanding of these factors and more information as to the methods of taking them into account has increased during recent years on account of the performance requirements of modern relaying schemes designed to provide more effective assurance of uninterrupted service. Furthermore, where there are multiple interconnected secondary circuits with totalizing phase and residual burdens such as result, for example, in a bus differential scheme of protection, there is the additional problem of determining the current distribution in the various branches of the secondary circuit for both balanced and unbalanced fault conditions.

The manner in which the ratio and phase relations of the secondary current to the primary current are affected by the components of current required for the excitation of the core and to supply the losses for steady-state conditions is well known,[1] but it is necessary for design and operating engineers to have more complete data than heretofore available, and to be provided with suitable methods of calculating the over-all performance under various conditions which may exist in the field. Similar information is also required regarding the performance during transient conditions but this phase of the problem is beyond the scope of this paper.

In order to obtain the necessary data regarding the performance of a particular relaying scheme, a series of extensive laboratory tests was made on a specific type of multiratio bushing current transformer for various secondary conditions. The purpose of this paper is, first, to present the more important results of these tests, and second, to show that the results so obtained can be calculated with reasonable accuracy from the in-phase and quadrature components of the excitation curves.

Some information regarding the wave-shape distortion of the secondary current by reason of the excitation component was also obtained and data regarding this phase of the tests are given in this paper.

Description of Transformers and Classification of Tests

The current transformers upon which the tests were conducted are quite similar in design to those in general use, consisting of a circular laminated core of silicon steel, a secondary winding with taps for different turn ratios, and a single-turn primary formed by the stud of the oil circuit breaker passing through the center of the core. By proper selection of the taps, turn ratios from 10 to 1 up to 120 to 1, with the exception of 70 to 1 and 110 to 1, may be obtained. In order to obtain better operating characteristics, these transformers were designed specifically to have larger core volumes than had previously been used.

For the purpose of this paper, the tests that were made may be classified and briefly outlined as follows:

(a). Ratio and phase-angle tests for different turn ratios and burdens.

(b). Single-circuit tests to determine the magnitude and phase relation of the current in each portion of the interconnected secondary circuits, and under conditions equivalent to a line-to-ground fault. The tests were made for three different turn ratios and for several different burdens.

(c). Double-circuit tests, similar to the preceding single-circuit tests.

(d). Miscellaneous tests, such as excitation curves of the transformers, the taking of oscillograms during the tests, and the determination of the burden characteristics.

Test Equipment and Procedure

Inasmuch as a high degree of accuracy such as is required for billing metering was not deemed necessary for the intended purposes, practically all of the tests were carried out with portable voltmeters, ammeters, wattmeters, and previously standardized instrument transformers.

The primary bus currents were obtained from low-voltage loading transformers, the primary voltage of which was controlled by a 25-kva single-phase induction regulator. Although this voltage regulator was overloaded during some of the tests, involving the higher burdens, and caused some distortion of the primary voltage and current waves, there is good reason to consider, as will be shown later by the closeness of calculated values with actual test values, that the results of the tests were not affected seriously by reason of the distortion that was introduced in the primary currents of the transformers. It is believed that the very presence of distortion for the higher current values actually aided in arriving at some important conclusion as to the amount of distortion introduced in the secondary current by reason of the large third harmonic component required by the excitation component of the primary current.

All of the oscillograms shown in the accompanying figures were obtained from a cathode-ray oscillograph, having a photographic attachment. A number of check oscillograms, however, were taken with a magnetic type of oscillograph and it was found that there was a substantially close agreement of the waves obtained with the two different types of oscillographs.

Burdens

Three different types of burdens were used during the tests: (1) variable nonsaturating burdens capable of carrying secondary currents up to 80 amperes; (2) nonsaturating burdens of lesser carrying capacity for the portions of the interconnected secondary circuits in which the secondary current did not exceed 10 amperes; and (3) saturating burdens made up of relay coils, compensator coils, and other iron-core reactive devices. It was the intention at first to use actual relays for the saturating burdens, but it was found that the windings could not stand the heavy secondary currents for the period of time

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1. For all numbered references, see list at end of paper.

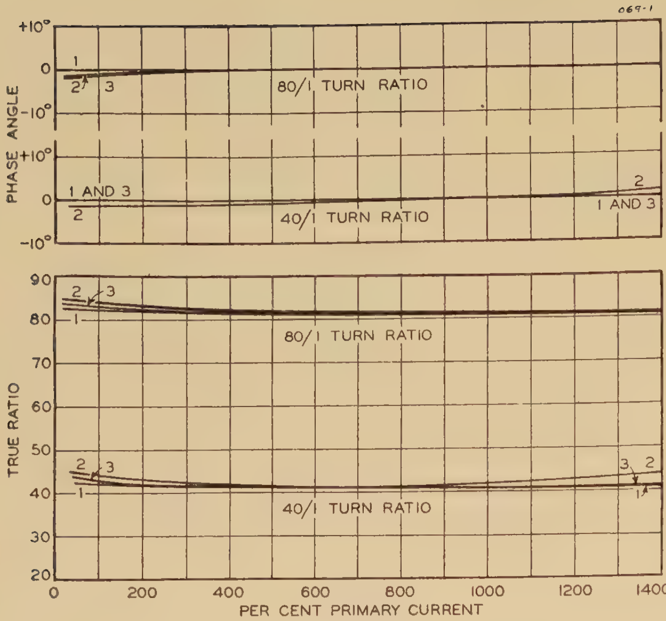


Figure 1. Phase-angle and ratio characteristics

Nonsaturating burdens, 40/1 and 80/1 turn ratios

Curve 1—18 volt-amperes, 0.5 power factor, single transformer

Curve 2—50 volt-amperes, 0.5 power factor, single transformer

Curve 3—50 volt-amperes, 0.5 power factor, two transformers in series

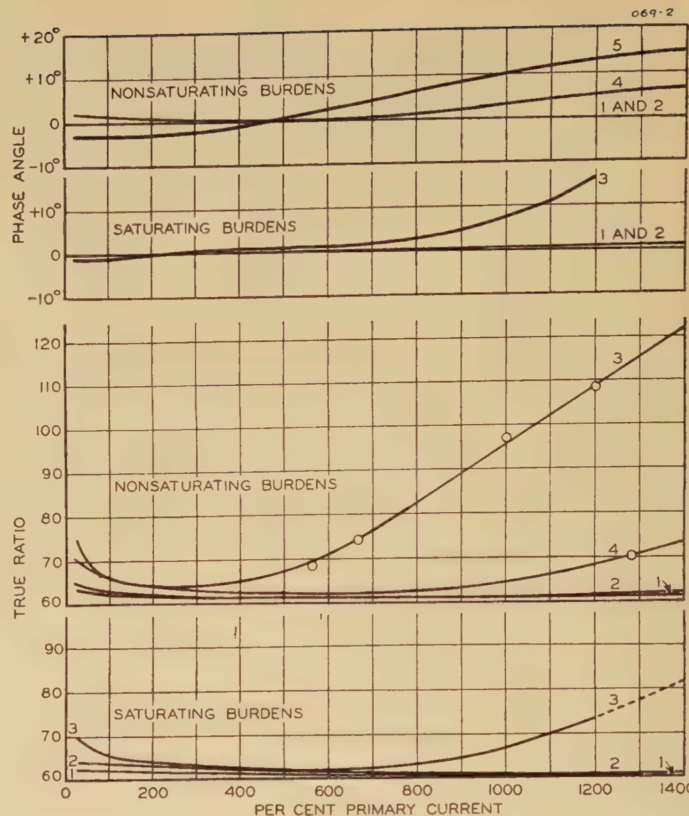


Figure 2. Phase-angle and ratio characteristics

Saturating and nonsaturating burdens, 60/1 ratio

Curve 1—18 volt-amperes, 0.5 power factor

Curve 2—50 volt-amperes, 0.5 power factor

Curve 3—200 volt-amperes, 0.5 power factor

Curve 4—100 volt-amperes, 0.5 power factor

required to take the various instrument readings.

Single-Phase Ratio and Phase-Angle Characteristics

Figures 1 and 2 show the ratio and phase-angle characteristics for three different turn ratios—namely 40:1, 60:1, and 80:1. There does not appear to be much necessity to enter into any detailed analysis of these curves, excepting to call attention to the fact that while in this type of current transformer there is a greater deviation from true ratio and phase angle at values of current near rated current than is permissible in instrument transformers, the reverse is true for the higher values of current. Relay performance is usually associated with current magnitudes well above the rated current of the transformer, and from this standpoint the bushing current transformer is superior to an instrument type. There are, however, cases where relays are required to operate at values of current approaching full-load current, so that the entire performance curve is of importance. The curves also bring out the fact that, particularly for relatively heavy burdens at poor power factor, the ratio and phase-angle characteristics are much better for the higher turn ratios than they are for the lower ones, and a real advantage can frequently be gained by using the higher turn ratios.

In order to show to what extent the ratio and phase-angle performance has been improved by using the extra-volume cores, it would undoubtedly be interesting to present at this point some corresponding curves for transformers having smaller volumes. Unfortunately, such data are not readily available but an equation has been derived from the test data which expresses the approximate relation between a change in volume from a reference volume and the ratio of the primary current to the secondary current. This equation, together with its derivation, is given in the appendix.

A number of tests were made on two transformers with their secondaries connected in series, curves of which are given in figure 1 and show that for burdens of less than 50 volt-amperes and with turn ratios above 40:1, there is little gain in actual accuracy, at least for the primary currents that have been considered. From the test results, and also from the equation that has been deduced for the volume-ratio relation, it appears that the ratio curves that will be obtained for two transformers with their secondaries in series for a certain burden, are approximately the same as is obtained with one transformer with half that burden.

The curves so far discussed apply to nonsaturating burdens. In figure 2, curve 3, the ratio and phase-angle curves are shown for a 200-volt-ampere saturating burden, on the basis of a five-ampere rating. During the tests, a complete record was kept of the volt-ampere burden that the saturating burdens imposed upon the secondary and it was found that a nominally rated 200-volt-ampere saturating burden actually imposed the equivalent of a 110-volt-ampere nonsaturating burden at 55 amperes secondary current. This change in the relative value of the burden will explain why the curve for a 200-volt-ampere saturating burden corresponds very closely to the curve for the 100-volt-ampere nonsaturating burden. Inasmuch as the burdens obtained in actual installations have in general saturating characteristics of widely varying degree, it may be important in some cases that these saturating characteristics be known and taken into consideration.

It is, of course, to be understood as previously stated that the test results apply only for steady-state conditions. Some information regarding the performance of current transformers under transient conditions, particularly for primary currents within the rating of the transformers, has been published.[1–3] In conducting the

tests described herein, due precautions were taken to eliminate any residual magnetization of the cores which might affect the results of the tests.

Calculation of Ratio and Phase-Angle Characteristics

It is generally accepted that in the case of standard types of instrument transformers operating below the saturation point, the ratio and phase-angle characteristics can be calculated from the excitation characteristics and give results that are in substantial agreement with actual test data.

The symmetrical form of the core of the bushing transformers and the practically uniform distribution of the secondary winding, at least for the higher turn ratios, gave reason to consider that it should be possible similarly to calculate their ratio and phase-angle characteristics. This is very desirable because of the expense and equipment necessary to make actual tests, especially at the higher current values.

Figure 3 shows the in-phase and quadrature components of the excitation current as obtained in the test made on the secondary side with 40:1, 60:1, and 80:1 turn ratios. In these excitation tests, the current values were measured by dynamometer ammeters. The voltages for the lower values were measured with a combination of a high-resistance rectifier voltmeter and ratio box. This combination was checked for each reading against a dynamometer voltmeter and care was taken to insure that the check test was made under practically the same voltage wave form as in the actual test. The relative proportion of in-phase and quadrature components of the excitation current was obtained by calculation from the watt loss measurements and the volt-ampere values. The power measurements were made with wattmeters having high-resistance voltage circuits and the readings were duly corrected for the losses in the test instruments themselves, the amount of which was very considerable at the lower values of excitation current.

The procedure for calculating the ratio and phase-angle characteristics from the excitation data is well known and fairly simple. Starting with a definite value of secondary current, the voltage necessary for a specific secondary burden is calculated. For accurate results the leakage reactance of the secondary winding itself should be taken into consideration in calculating the required secondary voltage. For the transformers under consideration the combined effect of the secondary resistance and leakage reactance was approximately 0.1 ohm and is practically constant for the three turn ratios of 40:1, 60:1, and 80:1. Knowing the voltage required, the corresponding excitation components are obtained from the excitation curve and added vectorially to the secondary current and the resultant multiplied by the turn ratio to obtain the corresponding primary current. Five or six such calculations for different secondary currents are generally sufficient to obtain the ratio curve. The encircled points shown in figure 2 indicate the calculated values as obtained by this procedure. If the calculations are made by the rectangular-component method, with the induced voltage taken as the reference axis, the phase angle between the secondary current and the primary current reversed can be determined.

Inasmuch as bushing current transformers are in general provided with a number of taps on the secondary winding, in order to obtain various turn ratios, it was considered desirable to determine whether the excitation curve for a certain turn ratio would be applicable for other turn ratios. For conditions below saturation, the excitation current may be considered approximately inversely proportional to the square of the turn ratio, but for conditions in the saturation region, this relation does not hold true, and hence in using the excitation curve of a particular turn ratio for calculating the values for some other turn ratio, it is found necessary to modify the procedure for calculating the excitation components.

Designating as N_1, the turn ratio for which the excitation curves are available and as N_2 the turn ratio for which the corresponding curves are desired, the first step is to obtain the excitation values for voltage values equal to $E \times N_1/N_2$ and the second step to multiply the values so ob-

Figure 3. Excitation curves

Points for 40/1 ratio calculated from 60/1-ratio curve

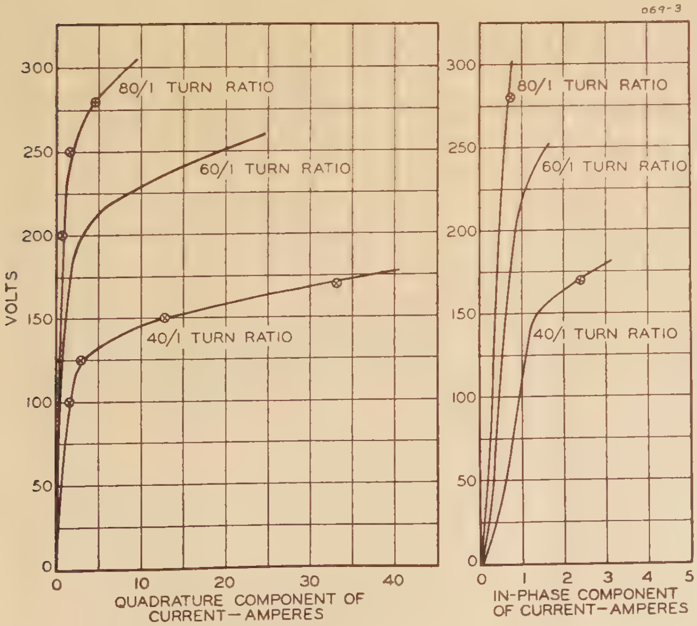
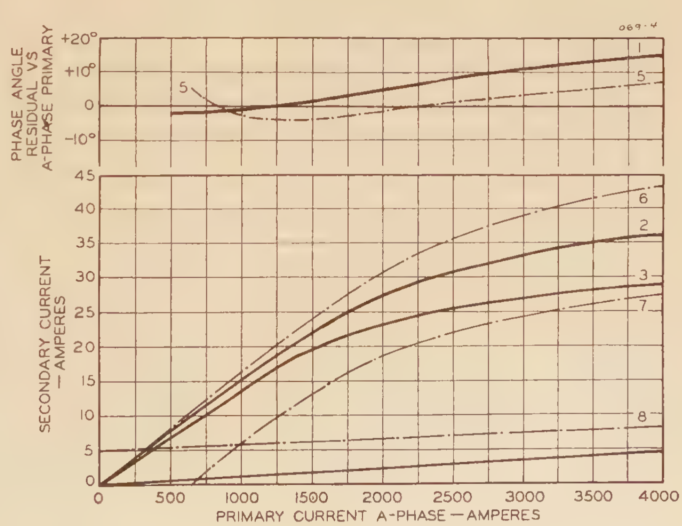


Figure 4. Current division for circuit shown in figure 6a

Nonsaturating burdens; 200 volt-amperes, 0.5 power factor residual circuit; 18 volt-amperes, 0.5 power factor each phase circuit

Zero current in primaries *B* and *C*:
Curve 1—Phase angle
Curve 2—*A*-phase secondary
Curve 3—Residual
Curve 4—Average *B* and *C* secondary

300 amperes in primaries *B* and *C*:
Curve 5—Phase angle
Curve 6—*A*-phase secondary
Curve 7—Residual
Curve 8—Average *B* and *C* secondary



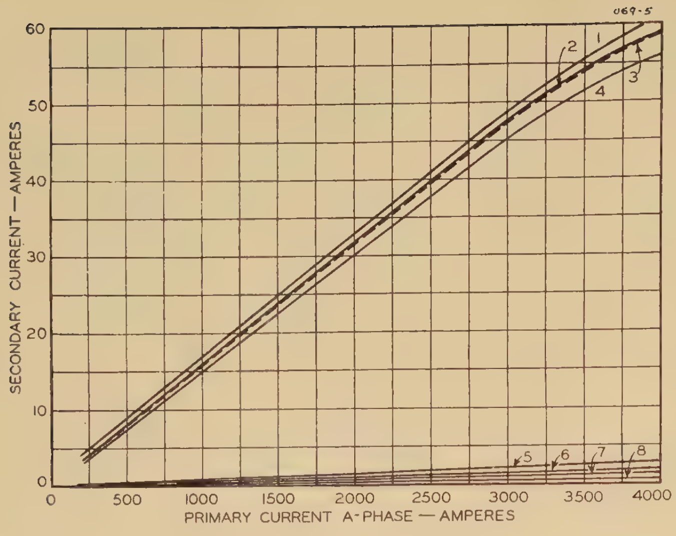


Figure 5 (left). Current division for circuit shown in figure 6c

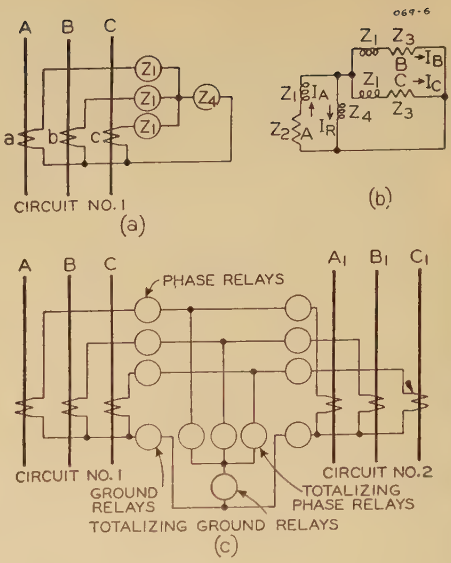


Figure 6 (right). Typical circuits involving interconnected secondary circuits

Nonsaturating burdens; 50 volt-amperes, 0.5 power factor totalizing residual circuit; 18 volt-amperes, 0.5 power factor each phase circuit; 18 volt-amperes, 0.5 power factor each phase totalizing circuit; zero volt-amperes each circuit residual

Zero current in all primaries except phase *A*

Curve 1—*A*-phase circuit number 1 secondary
Curve 2—*A*-phase totalizing
Curve 3—Residual circuit number 1
Curve 4—Totalizing residual
Curve 5—Residual circuit number 2
Curve 6—*B* or *C* phase totalizing secondary
Curve 7—*A*-phase circuit number 2 secondary
Curve 8—Average *B* and *C* secondary circuits 1 and 2

tained by N_1/N_2. The result gives the excitation components for the N_2 turn ratio at E volts. The encircled points in figure 3 show the calculated values of the excitation components for the 40:1 and 80:1 turn ratios obtained from the 60:1 excitation test curves by the above procedure.

Distribution of Current in Interconnected Secondary Circuits

The determination of the distribution of current in the interconnected secondary circuit for various relaying schemes presents a more complicated problem. Tests were made for two representative circuits, one, figure 6*a*, for a single three-phase circuit with phase and ground relay burdens, and the other, figure 6*c*, for two three-phase circuits with individual phase relay burdens and totalizing phase and ground relay burdens. The tests were made simulating fault conditions resulting in current in one primary conductor only and also for faults in which there is a relatively small current in the two unfaulted conductors. The results of these tests are shown by the curves of figures 4 and 5.

In addition to providing information as to the distribution of current for the particular current transformers and burdens tested, a study of the results has been of assistance in arriving at analytical methods of calculating the distribution of current in similar circuits from the excitation characteristics of the current transformers and the impedance of the various burdens. It may be safely assumed that whatever current will flow through the idle secondaries will be in the nature of an excitation current and that no appreciable power or apparent power will be transformed to the respective primary windings of the two transformers. In other words, the impedance offered by each of these idle secondary windings is the same as the excitation impedance. In the case of primary currents in each of the three phases, a solution is obtainable by making calculations for each primary current separately, assuming no current in the other two primary conductors. The final result may then be obtained by superimposing the three separate solutions numerically or, if necessary, vectorially.

Referring to figure 6, let it be assumed that the secondary current I_A is due to a given primary current in the A conductor and that the other two primary currents are zero, the assumed condition representing a line to ground fault in which the two unfaulted line conductors carry no current.

The current I_A will be distributed in the other portions of the interconnected circuit in inverse proportion to the respective impedances of each branch. The impedance offered to the flow of any part of I_A by each of the two otherwise-idle secondary windings will depend primarily upon the voltage available at their respective terminals and their excitation characteristics. If the available voltage at the terminals of the windings can be determined, the value of the corresponding current may be obtained from the secondary excitation current and voltage relation. Therefore, in order to analyze the distribution of current in the interconnected circuit, it is necessary to determine the relative value of this voltage with respect to the current that may flow. Such a relationship may be deduced very readily for the simple circuit shown in figure 6*a*. For a more involved circuit, as for example that shown in figure 6*c*, the solution may be obtained by successive approximations. Although a rigorous solution may undoubtedly be

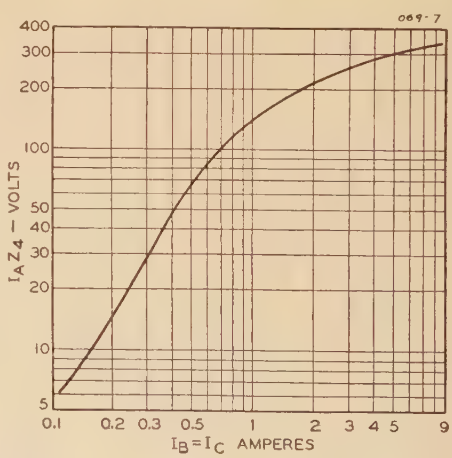


Figure 7. Curve showing current diverted from the residual circuit by each of the two idle secondary branch circuits B and C of figure 6b

$$I_A Z_4 = I_B(Z_1 + 2Z_4) + E_3$$

formulated for any interconnected secondary circuit and a family of curves plotted by means of which the division of current may be determined graphically, such a solution will not usually be found to be

necessary because of the uncertainty of the accurate determination of other factors, as for example, the value of the fault current itself. It is for this reason that it is considered that certain other assumptions are justifiable.

In the treatment which follows, the assumption is made that if the power factor of all the secondary burdens be considered to be approximately 0.5, then the secondary current and the excitation current through the idle secondary windings may be added numerically instead of vectorially and thereby lead to a simplification of the problem and still give results that appear to be sufficiently accurate for the intended purposes. With the assumptions that have been mentioned, the following analysis has been made using figure 6*b*, which is the simplified circuit for figure 6*a*.

Legend

Z_t = total impedance imposed on the A secondary winding

I_A = secondary current in the A secondary winding due to primary current in phase A. Primary current in phases B and C equal to zero

E_1 = total voltage induced in the A secondary winding

E_2 = voltage available at terminals of branch circuits

E_3 = voltage available at terminals of idle secondary windings

The other symbols used below are shown in figure 6*b*.

$$Z_t=(Z_1+Z_2)+(Z_1+Z_3)Z_4/D \quad (1)$$

$$D=Z_1+Z_3+2Z_4 \quad (2)$$

$$E_1=I_AZ_t \quad (3)$$

$$E_2=E_1-I_A(Z_1+Z_2)=I_A(Z_1+Z_3)Z_4/D \quad (4)$$

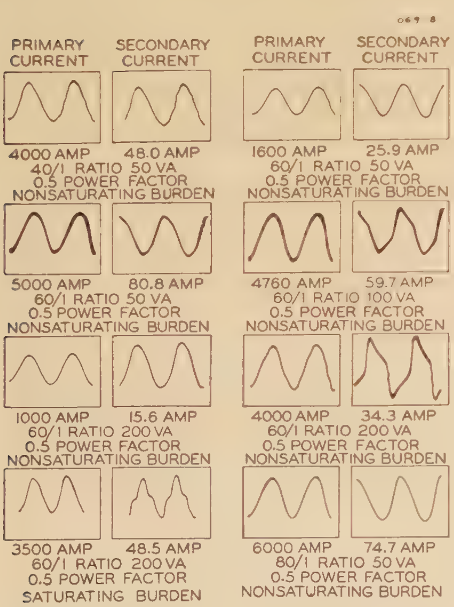
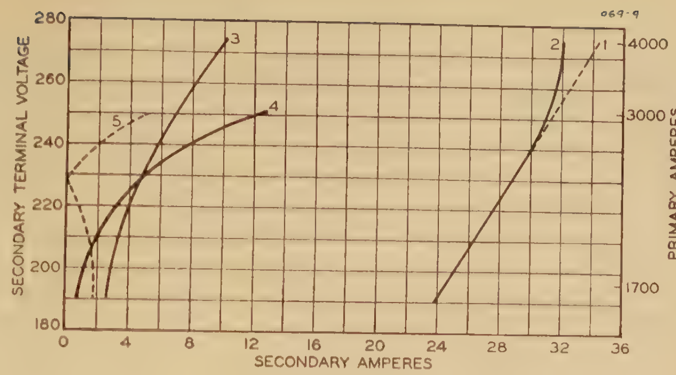


Figure 8. Oscillograms of typical primary and secondary current wave shapes

Figure 9. Relation of fundamental and third harmonic components of secondary current

200-volt-ampere nonsaturating burden, 60/1 turn ratio



$$I_B=I_C=I_AZ_4/D \quad (5)$$

$$I_R=I_A(Z_1+Z_3)/D \quad (6)$$

$$E_3=E_2-I_BZ_1=I_AZ_3Z_4/D \quad (7)$$

Substituting E_3/I_B for Z_3 in equation 7 and simplifying, gives:

$$I_B(Z_1+2Z_4)+E_3=I_AZ_4 \quad (8)$$

Since the values I_B and E_3 are related by the excitation curve, new curves may be drawn for $I_B(Z_1+2Z_4)+E_3$ versus I_B and from such a curve the value of I_B corresponding to the value I_AZ_4 may be found.

Figure 7 shows such a curve and it is derived from the excitation curve for the 60:1 turn ratio. The burden values Z_1 and Z_4 are taken as 0.8 and 8.0 ohms respectively, the same as were the values of the burdens used in the interconnected secondary circuit in the test for which curves are shown in figure 4. A curve closely approximating curve 4 in figure 4 can be obtained by means of the curve, figure 7.

In the case of the double interconnected circuit shown in figure 6*c*, the best procedure appears to be to start with a first approximation of the current in the residual circuit and proceed to the other branches, using a voltage and current relationship as was done for the simple circuit. In connection with this particular interconnection, attention is called to the possibilities that the amount of current diverted away from the totalizing residual circuit by the A_1 branch circuit may reach values equal to or even greater than the residual current itself if the burdens of the phase relays and circuit ground relays are low compared to the totalizing ground relays.

Wave Distortion of Secondary Current

The excitation component of current introduces not only ratio errors and phase-angle displacement but also affects the secondary-current wave shape. During the tests, numerous oscillograms were taken of the primary current, the secondary current, and the secondary induced voltage.

Curve 1—Secondary current, equivalent sine wave

Curve 2—Secondary current, 60-cycle fundamental

Curve 3—Secondary current, third harmonic

Curve 4—Excitation current, third harmonic on secondary basis

Curve 5—Third harmonic in primary current on secondary basis

Additional oscillograms were also obtained of the excitation current. Most of those which showed considerable distortion were analyzed for the fundamental, the third, the fifth, and the seventh harmonic components. A number of these oscillograms are given in figure 8.

The theory of wave distortion by transformers in general and its effect on relay operation has been discussed in previous publications[1,4] and only a brief discussion of the test results is given here. It will be noted from the oscillograms that the distortion is very small for the low burdens. In the case of a 50-volt-ampere burden and with 60:1 turn ratio, the distortion in the secondary current does not become noticeable until the primary current reaches a value of 5,000 amperes, or 16.7 times the normal primary-current rating. In the case of the 200-volt-ampere burden, distortion begins at about 1,200 amperes, or four times the normal rating.

The curves in figure 9 which show the actual values in amperes of the fundamental and the third-harmonic component in the secondary current for different values of secondary-terminal voltages, were obtained by analyzing the oscillograms made during the tests on the 60:1 turn ratio and a 200-volt-ampere nonsaturating burden. Curve 4 in this figure was plotted from the excitation-current waves obtained during the excitation-current tests on the 60:1 turn ratio. The dashed curve number 5, shown in this figure, represents the difference between the third harmonic component actually required for excitation (on a secondary basis) and the amount of the third-harmonic component

in the secondary current. This difference would seem to indicate the amount of third-harmonic current present in the primary current, and appears to have been due to the single-phase induction regulator used in the test to regulate the primary voltage applied to the loading transformers. It is interesting to note that for the condition of minimum third-harmonic component in the primary current the regulator was near the position where minimum distortion may be expected.

Analyzing the matter further, it appears tenable to state that the amount of the third-harmonic component in the secondary current is approximately equal to the vector difference of the third harmonic actually present in the primary current and the amount of third-harmonic current actually required for excitation, all values reduced to a secondary basis. Hence, the further deduction that if the fault current during a line-to-ground fault is sinusoidal, then the amount of third-harmonic component present in the secondary current should be equal to the third-harmonic component required for excitation. Although this would be true only if the burdens are nonsaturating, nevertheless, it would appear from the analysis of some of the oscillograms that with saturating burdens, the amount of the third harmonic is not altered very greatly from that with nonsaturating burdens, excepting that there is a different phase displacement of the third-harmonic component with respect to the fundamental which results in a more peaked secondary-current wave for saturating burdens than is the case for nonsaturating burdens.

As to the fifth and higher harmonics, no attempt was made to correlate the results, mainly because the analyzation of the waves for such harmonics could not be carried out within a reasonable degree of accuracy.

Conclusions

Although this series of tests was made on a specific set of bushing current transformers, an analysis of the results leads to certain conclusions which are applicable to this general type of transformer. These may be summarized as follows:

1. Bushing current transformers having cores of adequate volume and reasonably high turn ratios have characteristics which are very desirable from the standpoint of relay application and in some cases may be superior to instrument-type transformers.

2. The performance characteristics of bushing current transformers can be determined with reasonable accuracy from the in-phase and quadrature components of the excitation current.

3. The distribution of current in circuits involving interconnected transformer secondaries can be arrived at by a consideration of the impedance of the burdens in the various branches of the secondary circuit and the excitation characteristics of the current transformers. For various primary circuit conditions a solution is obtainable by making calculations for each primary current separately, assuming no current in the other primaries, and then combining results.

4. The effect of increasing the volume of the core of a bushing transformer by a certain per cent is equivalent to decreasing the burden by a like per cent. Likewise, the use of two bushing transformers in series is equivalent to reducing the burden on one to half the total burden.

Appendix

True Ratio Versus Change in Core Volume

The relation of the true ratio versus change in core volume, is a function of the excitation current required for a particular burden. If the volume is increased by changing the axial dimension and the radial dimensions remain the same, the magnetic cross section will be increased correspondingly and hence for a given number of turns in the secondary winding and for a given excitation current, the flux and the voltage induced by the flux, will be increased in the same proportion. The iron losses will of course enter into consideration but it can be shown that the effect is negligible.

For instrument transformers which generally operate below the knee of the saturation curve, factors other than the true ratio, in general, determine the core dimensions. In the case of bushing current transformers with low ampere-turn ratings, the ratio accuracy is one of the important factors which determine the core dimensions. Inasmuch as this discussion is concerned mainly with reference to conditions in the saturated region, it is of interest to analyze the relationship of the true ratio with respect to changes in the core volume, for such conditions only.

For such an analysis, the portion of the excitation curve above the knee may be represented by an equation of the form $I=k_1E/(1-k_2E)$. Now if V_1 represents a reference volume and V_2 the volume for which the ratio characteristics are desired, then if the change in volume from V_1 to V_2 is a change in the axial dimension only, the respective excitation currents, of the two volumes, will be:

For volume V_1,

$$I_{e1}=k_1E_{s1}/(1-k_2E_{s1}) \tag{9}$$

For volume V_2,

$$I_{e1}=k_1E_{s2}V_1/(V_2-V_1k_2E_{s2}Z) \tag{10}$$

The values E_{s1} and E_{s2} may be replaced by the respective products $I_{s1}Z$ and $I_{s2}Z$ in which I_{s1} and I_{s2} are the respective secondary currents and Z is the impedance of the secondary burden.

For the purpose of this analysis, the secondary burden is considered to have a power factor of 0.5 and on this basis the assumption is made that the excitation-current component and the secondary current are close enough in phase to permit adding their values numerically instead of vectorially. The respective true ratios for the two volumes are then given by equations 11 and 12.

$$R_1=N\left(1+\frac{k_1Z}{1-k_2ZI_{s1}}\right) \tag{11}$$

$$R_2=N\left(1+\frac{k_1ZV_1}{V_2-V_1k_2ZI_{s2}}\right) \tag{12}$$

Substituting $I_{p1}=R_1I_{s1}$ and $I_{p2}=R_2I_{s2}$ in the two preceding equations, and equating the two for $R_1=R_2$, gives the following relationship of the primary currents:

$$I_{p2}=I_{p1}+\frac{(V_2-V_1)}{V_1}\,\frac{R_1}{K_2Z_1} \tag{13}$$

Hence, if the corresponding values of I_{p1} and R_1 are known for volume V_1, the corresponding primary current I_{p2}, for which the true ratio is equal to R_1, may be calculated. The value of the constant k_2 may be determined from the excitation-current curve.

The conclusion that may be deduced from curves plotted by means of equation 13 may be stated in various ways but it would seem that the following would best serve the purpose, namely, that the gain in ratio accuracy that is obtained by increasing the axial dimension of the core by a certain percentage is approximately the same as would be obtained with the original volume by reducing the value of the burden the same percentage.

Ratio Versus Burden Impedance

For approximate determination of the ratio curve for a burden of Z_2 ohms impedance, if the curve is known for a burden of Z_1 ohms and of the same power factor as Z_2, the following equation has been found to give sufficiently accurate results for conditions in the saturating region.

$$I_{p2}=I_{p1}+\left(\frac{Z_1-Z_2}{Z_2}\right)\frac{R_1}{KZ_1}$$

The value of the constant k is the same as in the preceding equation 13.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

A Proposed Method for the Determination of Current-Transformer Errors

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CURRENT TRANSFORMERS for relay service must be able to function with reasonable accuracy under very high overload conditions, and it is therefore necessary that their accuracy for such high currents be verified. However, in performing the usual accuracy test at very high currents, certain difficulties are encountered—the principal ones being:

(*a*). The difficulty of providing large amounts of power at large current values and bus-bar type wiring required. The kilovolt-amperes required at 20 times normal current is 400 times that at normal current.

(*b*). The necessity for standard burdens capable of withstanding heavy currents.

(*c*). The necessity for taking the meter readings very rapidly—within a few seconds—in order to avoid overheating of the current-transformer windings.

This paper proposes an indirect method for determining the accuracy characteristics—phase angle and ratio—of a current transformer for both normal and abnormal currents, whereby the difficulties of test mentioned above are obviated, with no sacrifice of essential accuracy. It consists in the determination by test of the impedance and of the excitation characteristics of the transformer and calculating from them the ratio and phase-angle errors of the transformer.

In this respect the proposed indirect method, as a method of calculation of the *current* regulation of the transformer, falls in identically the same category as the standard procedure for determining the voltage regulation of a power transformer indirectly from impedance measurements.

Equivalent Circuit of a Transformer as Reduced to 1:1 Ratio

The errors of a current transformer arise from the fact that not all of the primary current is transformed, a component (I_e) being used to excite the core. This may be seen more clearly by referring to the conventional equivalent circuit of a transformer as shown in figure 1. In this diagram R and X are respectively the resistance and the reactance of the external burden, and r_1, r_2, x_1, x_2, respectively the resistances and reactances of the primary and secondary windings.

The exciting current is conceived of as occasioned by a load in a fictitious third winding. From the equivalent circuit it is easily seen that the value of the by-passed exciting I_e depends upon the value of the induced voltage E_2, and it follows therefore that the characteristics of a current transformer are defined when the values of r_1, r_2, x_1, and x_2 are known and the exciting current I_e is given as a function of E_2.

For if these values are known, then it follows from the equivalent circuit that:

$$I_2 = I_1 - I_e \qquad (1)$$

and:

$$E_2 = I_2\{(r_2+R)+j(x_2+X)\} \qquad (2)$$

and consequently the ratio $|I_2|/|I_1|$ and the phase angle $(\angle I_2 - \angle I_1)$ can be determined as illustrated below.

Determination of the Leakage Reactances

Of course r_1 and r_2 can be measured directly across each winding. In order to be able to measure the primary and secondary leakage reactance voltages directly it is necessary that there be only load currents in the windings and no exciting current—that is, the primary and secondary ampere turns must be exactly equal and opposite. This condition can be realized in a 1:1 ratio transformer by connecting the primary and the secondary windings in series opposition and forcing the desired current through them.[1] The voltages measured across each winding are then caused respectively by the "primary" and "secondary" internal impedances of the transformer. Knowing the current, the leakage reactances x_1 and x_2 can be calculated.

To insure equality of primary and secondary ampere turns in transformers other than 1:1 ratio, some expedient must be introduced. One such method is illustrated in figure 2. This figure shows a bushing-type current transformer. However, the scheme can be used for any current transformers provided they do not incorporate methods of compensation other than the regular turn compensation. In figure 2, B is the transformer of which it is desired to determine the secondary leakage reactance; A is an auxiliary current transformer which is used to balance the primary and the secondary ampere turns of the transformer B.

The auxiliary "balancing" current transformer A is wound with suitable taps and its ratio of transformation is chosen to be *identical* with that of current transformer B under test. The auxiliary current transformer A has also an exploring winding $N4$ which is connected to a vibration galvanometer.

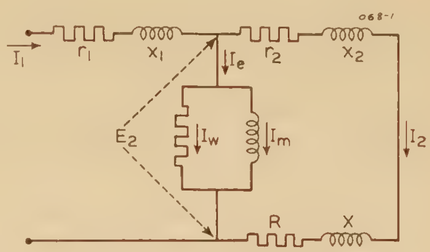

Figure 1. Equivalent circuit of a current transformer

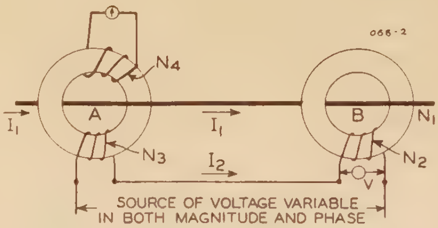

Figure 2. Method for determining the secondary impedance of a current transformer

The primary winding of the transformer to be tested is connected in series with the primary winding of the balancing transformer and to a source of voltage supplying the primary current. Likewise the secondary windings of the transformers are connected in series and to a source of voltage supplied by a phase shifter.

The phase and magnitude of the current supplied by the phase shifter are ad-

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1. For all numbered references, see list at end of paper.

justed until the flux in the balancing transformer is zero. This is determined by a zero reading on the vibration galvanometer. The value of I_2 is measured by an ammeter and the voltage V by a voltmeter, across the secondary of the

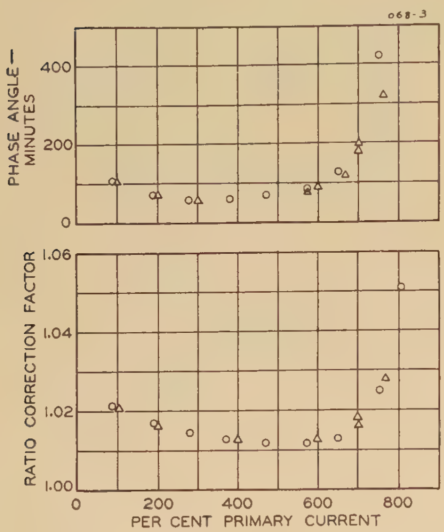

Figure 3. Comparison between calculated and test results, 300-ampere current transformer number 1, 60-to-1 ratio

Bushing type with distributed secondary winding; burden 50 volt-amperes, 100 per cent power factor, 60 cycles

⊙—Calculated △—Test

transformer B. The latter is proportional to the internal secondary impedance of the transformer.

The balancing transformer is preferably of ring form with its primary and secondary windings uniformly distributed so that magnetic leakage is reduced to a minimum.

It has been stated that the balancing transformer of figure 2 needs to be of the same ratio as the current transformer under test. To fulfill this requirement it is necessary to know the secondary number of turns of the current transformer. There are several ways in which this can be obtained by test,[2] but the description of these methods falls outside the scope of this paper. Of course the simplest way is to obtain this information directly from the manufacturer.

In these tests, two methods were used for obtaining the variable source of voltage:

(*a*). By deriving this voltage from a conventional phase shifter (a wound-rotor polyphase induction motor will serve)

(*b*). By the use of two generators the shafts of which are connected mechanically. The stator of one of the generators can be turned with respect to the other

The voltmeter V needs to be of very high resistance. A good plan is to use a copper-oxide voltmeter having an internal resistance of about 1,000 ohms per volt. The Tinsley-Gall a-c potentiometer can also be used to read the above voltage.

Variations of Secondary Reactance With Secondary Current of the Current Transformer

Theoretically the division of the leakage reactance of a transformer varies with the secondary current. The reason for this is that changes in permeability of the core at various densities affect differently the reluctances of the external and internal parts of the magnetic circuit—neither the iron magnetic circuit nor the air mag-

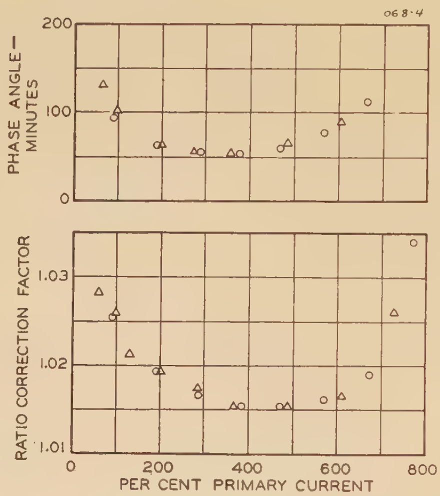

Figure 4. Comparison between calculated and test results, 300-ampere current transformer number 2, 60-to-1 ratio

Bushing type with secondary winding concentrated on approximately one-fourth of the circumference of the core; burden 50 volt-amperes, 100 per cent power factor, 60 cycles

⊙—Calculated △—Test

netic circuit, which are in parallel, having uniform section or length. It is found, however, by actual test that these changes are quite limited and not large enough to affect considerably the accuracy which can be obtained by the proposed method of test. Actual test results of the secondary reactance at two or more values of the secondary current are tabulated under the item of "Test Results".

Determination of Magnetic Properties of Core Material

In order to determine the performance of a given transformer under definite conditions of load, it is now necessary to obtain values of the watt and wattless components of the exciting current (I_e) corresponding to the voltage E_2 which is applied across the secondary terminals of the transformer. It should be noted from the equivalent circuit of figure 1 that theoretically to obtain the actual value of I_e corresponding to the induced voltage E_2 there should be applied across the terminals of the transformer a somewhat higher voltage; but in general the voltage drop caused by the current I_e flowing through the internal impedance of the transformer is very small and can be neglected.

In the measurements of watts and exciting current, the fundamental components of these quantities must be taken. In the tests made for the preparation of this paper, a Tinsley-Gall a-c co-ordinate potentiometer was used.[3] Other methods can be used when this equipment is not available. For instance, the fundamental component of the exciting current can be obtained by means of a separately excited wattmeter, the separate excitation furnished by a phase shifter.

Calculation of Current-Transformer Characteristics From Test Results

If the magnetic properties of the core of the current transformer and the leakage

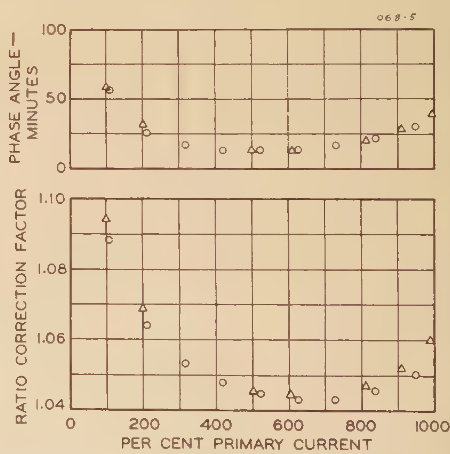

Figure 5. Comparison between calculated and test results, 200-ampere current transformer number 3, 40-to-1 ratio

Bushing type with secondary winding concentrated on approximately one-sixth of the circumference of the core; burden 50 volt-amperes, 100 per cent power factor, 60 cycles

⊙—Calculated △—Test

reactance of the secondary winding are known, the ratio and phase angle for any secondary current or burden on the current transformer can be calculated quite accurately.

Agnew[4] gives the following simplified formulas for calculating the errors in current transformers:

$$\text{ratio } (R)=\left(n+\frac{M \sin \phi+F \cos \phi}{I_2}\right)\frac{1}{\cos \theta} \quad (3)$$

$$\tan \theta=\frac{M \cos \phi-F \sin \phi}{nI_2} \quad (4)$$

where:

I_2 is the secondary current
n is the ratio of number of secondary to primary turns
θ is the phase angle of the current transformer
ϕ is the phase angle of the secondary current with respect to the induced voltage
M is the magnetizing component of the core exciting current
F is the corresponding loss component of exciting current (due to hysteresis and eddy losses in the core)

In order to obtain M and F it is simply necessary to multiply the wattless volt-amperes (VA) and the watts (W) respectively by:

$$\frac{n}{E_2}$$

After obtaining the internal secondary impedance of the given transformer and its excitation characteristics by the use of

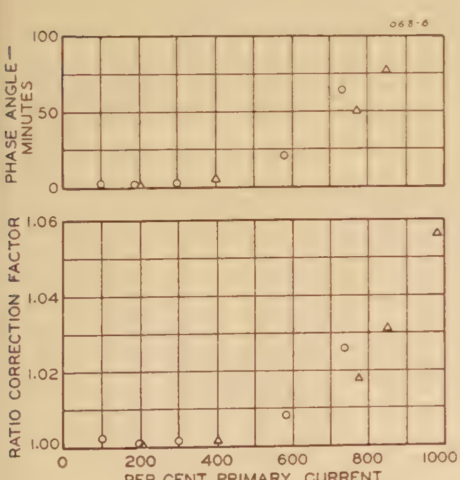

Figure 6. Comparison between calculated and test results, 100-ampere current transformer number 4, 20-to-1 ratio for 4,500-volt circuit

Wound-type current transformer; burden 50 volt-amperes, 50 per cent power factor, 60 cycles

⊙—Calculated △—Test

formulas 3 and 4 it is relatively a simple matter to determine the ratio and phase angle under any conditions of current and of burden. The method will be illustrated by an example and the results compared

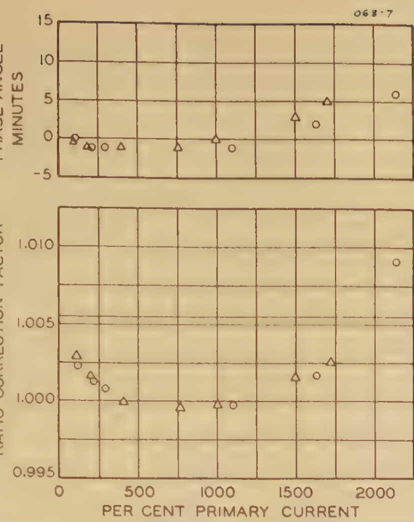

Figure 7. Comparison between calculated and test results, 50-ampere current transformer number 5, 10-to-1 ratio for 69,000-volt circuit

Wound-type current transformer; burden 50 volt-amperes, 50 per cent power factor, 60 cycles

⊙—Calculated △—Test

with test results obtained by a conventional method of testing.

Sample Calculation

To illustrate the method of test and the necessary calculations to determine the current-transformer errors, the following example is given:

Characteristics required on a bushing-type current transformer rated 300/5 amperes, having a concentrated secondary winding. Core dimensions—inside diameter = 8 inches, outside diameter = 10 inches, height = 3 inches
Secondary turns = 60

External burden = 50 volt-amperes at 100 per cent power factor

Balancing transformer consisting of a bushing current transformer having a core of the following dimensions: inside diameter = 16 inches, outside diameter = 20 inches, height = 3 inches. Secondary turns = 60 uniformly distributed over the core. Exploring winding of 100 turns—also uniformly distributed.

(a). Determination of Secondary Reactance

Test made at five amperes, 60 cycles
Voltage read across the secondary of the current transformer under test (at balance) = 1.70 volts
Measured secondary resistance of the transformer = 0.14 ohm
Calculated secondary reactance of the transformer = 0.31 ohm

(b). Test on the Magnetic Characteristics of the Core

For the sake of brevity only a few points are given:

E	W	I_e	F	M
60.12	20.64	0.775	20.58	41.70
70.32	29.62	1.31	25.50	74.4

(c). Calculation of the Characteristics of the Current Transformer

External burden—50 volt-amperes at 100 per cent power factor
$R=2 \quad X=0$
Internal burden—$r_2=0.14$, $x_2=0.31$
Total secondary impedance:

$R+r_2=2.143$
$X+x_2=0.31$
$Z\quad=2.16$

$$\cos \phi=\frac{2.14}{2.16}=0.99$$

$$\sin \phi=\frac{0.31}{2.16}=0.143$$

E	I_2	M sin ϕ	M cos ϕ	F cos ϕ	F sin ϕ	R	θ
60.12	27.8	5.98	41.3	20.4	2.94	60.96	78′
70.32	32.56	10.68	70.36	25.26	3.66	61.14	2°, 1′

Table I. Measured Secondary Impedances

Transformer Number	r_2	X_2	At I_2 (Amp.)	Remarks
1	0.132	0.002	5	
2	0.143	0.31	5	
3	0.083	0.274	2.3	
3	0.085	0.276	4.55	
3	0.084	0.274	7.83	
4	0.29	0.249	2	
5	0.52	3.65 3.48 3.30 3.19	2.68 4.79 7.3 8.7	Transformer compensated (Wilson method)
5	0.52	2.79 2.79 2.76	2.67 5.25 9.40	Transformer uncompensated

These results are compared with conventional test in figure 4.

Test Results and Discussion

The following transformers were tested:

1. Figure 3—bushing-type current transformer, wound core, secondary winding uniformly distributed. Ratio 300/5. Inside diameter of core = 8 inches

2. Figure 4—bushing-type current transformer, wound core, concentrated secondary winding—otherwise same as above

3. Figure 5—bushing-type current transformer, wound core, concentrated secondary winding. Inside diameter of core = 18 inches. Ratio 200/5

4. Figure 6—wound-type current transformer for 4,500-volt circuit. Ratio 100/5

5. Figure 7—wound-type current transformer for 69,000-volt circuit. Ratio 50/5. This transformer can be compensated according to the Wilson method. Tests were made with and without compensation

From table I it is noted that the secondary reactance of an annular core with distributed secondary winding is negligible, which confirms the findings of other investigators.[5] Table I and figures 3 to 7 also show that from a practical standpoint the secondary reactance is constant and a measured value at normal current can be used for overcurrent calculations, provided the transformer does not incorporate any compensating scheme other than simple turn compensation. With certain compensating schemes an estimation of this reactance can be obtained by testing at several points and extrapolating. This value can be used when errors are small.

The curves in figures 3, 4, 5, 6, and 7 show good agreement between test values and calculated values up to saturation of the core. The results obtained above saturation in either method (test or calculation) are somewhat indefinite. The method used for the testing recognizes only fundamental values of the primary and secondary currents. At these points above saturation, distortion is unavoidable. It is difficult to duplicate this distortion by calculation, and furthermore there is some doubt whether results in this region are of much value since some relays respond to fundamental values, some to effective values, some to peak values, and others to intermediate values. It should be pointed out, however, that overcurrent tests are more often used to compare the performance of two or more different current transformers and for such purposes the proposed method of indirect testing would appear satisfactory.

Conclusion

A method of testing current transformers has been described which eliminates a number of serious difficulties encountered in the usual methods of testing and is applicable with satisfactory accuracy under practically all current and burden conditions.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Railway Power Supply

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WHILE all industries depend on the use of power few are more vitally affected by the circumstances of its use than the transportation industry. In this industry power not only represents a large item in the total cost of operation but, by the varied forms and ways in which it can be applied, exercises an important influence in the creation of conditions favorable to more efficient movement of freight and passengers, improvement in the standards of service and resultant promotion of the business.

The determination of the type of power most advantageous in a specific case presents a multiplicity of problems which require detailed study by persons who possess extensive practical experience. In a general way, however, all engineers recognize the fact that, where electric power must be utilized in small quantities in widely separated locations, it is more economical to install the generating plant at the point of use. As these locations become more numerous and are grouped together, better results can be secured by generating the power centrally and distributing it to the individual users. Similarly, in generating power for the movement of trains, where they are limited in number and size the conventional method of using a steam locomotive or other power unit on each train is followed with satisfactory results. As the trains increase in number and size a point is reached where it becomes far more economical and satisfactory from every standpoint to install the power-generating facilities at a central location and supply the current to motors on the trains through a distribution system.

In any specific case the railroad executive will have to co-ordinate and evaluate all the gains possible from electrification but, in general, past experience has shown that it may be considered as a means of moving trains in dense-traffic territory at no additional cost and in many cases at considerable saving, while at the same time providing the public with faster schedules and more reliable service and the management with increased capacity of plant. The full benefits of a railroad electrification usually are not secured until after it has been in service for a sufficient length of time to enable the management, through education, training, and supervision, to take full advantage of the improved tool with which it is supplied.

As further experience is secured with railroad electrification the first cost and operating expenses should be materially reduced by using the same intensive methods of supervision and development which, in the past, have produced so much improvement in the service and reduction in the cost of steam operation. As these results are obtained, electrification will doubtless extend to portions of railroads which, under present conditions, are not considered to be suitable projects for this method of handling transportation; the intensified study which many power companies are giving to the subject of railway supply will help to make these results possible.

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Changing Aspects of Power Supply

When electricity first became available for traction, it found a ready field of application in the transportation of passengers in cities and towns and a new industry was soon developed in which it was used exclusively for motive power on account of its remarkable flexibility in handling such traffic. In the case of existing transportation systems, however, the substitution of electricity for steam encountered the serious obstacle that it would require large new investments, involving the addition of wayside structures, equipment and conductors, possible changes in track and facility provisions, and a complete change in locomotive equipment. For this reason the railroads found it more advantageous to continue their long-established policy of improving the economy of steam locomotives, designing different types for specific services and, more recently, of adopting internal-combustion engines for high-speed light passenger trains, for yard switching, etc. Nevertheless, in certain situations other weighty considerations made it desirable or necessary to adopt electric traction. This was the case in the early electrifications of important terminals serving considerable suburban passenger traffic and, later, where heavy freight traffic and steep grades, or the carrying of freight and passenger traffic in competition with other means of transportation, made the change to electric traction profitable.

In the foregoing developments, the role of the utilities in connection with the supply of power for traction, has passed through two different phases:

Many years ago, when electric traction was first introduced for urban rapid transit and, subsequently, for the more important steam-railroad terminals, the electric utilities were not sufficiently developed to supply advantageously throughout their territories, the large quantities of special current required for traction. Consequently the transportation companies, as a rule, installed their own plants and extensive distributing systems.

Later, because of their rapid growth, the utilities had greatly expanded their generating and distributing facilities and found themselves in a position to supply power to the transportation companies more advantageously than the latter could produce it. This change in conditions prompted the consummation of many contracts for the supply of power.

Type and Scope of Contracts

We shall subdivide these contracts into two types:

First—Those covering the supply of power to railways operating their own generating and distributing plants.

Second—Those covering power sales to railways to be electrified without power plants of their own.

A utility, in dealing with these two classes of contracts, is confronted with distinctly different problems. In the first case it has to prove to the prospective customer that its service will be more advantageous than can be obtained from his old plant even if it is improved by an economical modernization. In the second case the utility has to prove that its service will be more advantageous than the customer can obtain from a heavy investment in modern generating and distributing plant to provide the requirements of the road to be electrified.

First Case

Where the railways owned good-sized 25-cycle plants for generating their power requirements, and the utilities had considerable 25-cycle capacity installed for their own use, the parties were able to evolve special workable power arrangements based on interconnecting the railways' plants with the utilities. The less efficient railway plants were then operated for a minimum number of hours as in the case of the utilities' own generating capacity of older vintage, thereby realizing material operating savings which were equitably shared by both parties. In addition, the railways were relieved of the necessity of generating power, which must be a side issue for them since they are basically engaged in providing transportation, rather than in producing and distributing power economically.

These special power arrangements were dictated by the desirability of making full use of the unexpired economic life of the railways' plants without the necessity of large expenditures for their modernization, as is being successfully done on the utility systems, with assured increasing loads, by the installation of topping turbines. The railways are handicapped in carrying out a modernization program because it is generally difficult for them to dispense with a substantial part of their generating facilities during the protracted period required for reconstruction, and, if the construction plans are so worked out that the existing equipment is not disturbed the cost of the new facilities is likely to be excessive. Furthermore, since their rebuilt plants, in some cases, must be operated at the relatively poor traction load factor, they are not in a position to make the best use of the modern equipment and the operating savings may not be sufficient to counterbalance the added fixed charges. The utilities, by contrast, are in a position to modernize plants and to operate them advantageously for base-load generation, using the railway plants for emergency or standby service thereby filling the former role of the modernized plants. The old railway plants then readily fit in as a part of a co-ordinated program.

There is no standard form for such arrangements because the details to be covered vary greatly in each situation. Special provisions of the contracts usually are similar to those for straight power sales contracts hereafter described. The only essential requisite is that the net results must be such that the railways obtain the service at a lower cost than they could secure for themselves by modernizing their plants in order to raise their efficiencies to the standard afforded by the advancement in the art; and that the utilities obtain sufficient revenue to cover all operating expenses and fixed charges, including amortization of any new investment, plus allocated general expenses, taxes, and a fair share of the savings derived from the bulk production of the increased output. These savings will ultimately accrue to the benefit of the general customers in reduced rates.

Second Case

Contracts for the sale of power to traction companies not owning power plants are not essentially different from the usual form of "demand and energy rate" contracts and include such items as:

term of the contract—character of energy—points of delivery—use to be made of the energy—price of "demand" and "energy" charges—price adjustment for changes in cost of fuel, when power is produced by steam—definition of billing demands—service connections—billings and payments—etc.

In addition such important contracts also contain appropriate provisions, including:

dates for beginning specified partial services and full service—clauses to insure diligence in providing regular and uninterrupted service—access to records—testing of measuring instruments—arbitration—reduction of rates if more favorable rates are given other customers under substantially similar conditions.

In the preparation of each contract, the various provisions are carefully drafted to conform to the unique requirements of the case. Certain distinguishing

characteristics of railway contracts, and the considerations on which they are based, are as follows:

(*a*). A relatively long period of time is specified for the term of the contract and its renewals, if any.—These contracts being for large amounts of important service, it is obvious that the parties must have a relatively long period of guaranteed operation of the facilities provided for the service. Contracts are rarely written for less than 10 years and usually cover longer periods of operation up to 20 years with provision for extension of time should the utility make substantial additions to its facilities for the railway's use during the initial period.

(*b*). A guarantee of payment for a minimum amount of service each year is usually included.—The utility must have a guaranteed minimum payment in order to cover the overhead charges and provide, during the term of the contract, for reasonable amortization of the special investment made.

(*c*). Unusual methods of determining the monthly maximum demand for billing are used.—The operation of a railroad is subject to occasional large variations of maximum demand from causes extraneous to the normal operation. These fortuitous conditions should not be allowed to penalize the railroad unduly. Hence the average of the three highest clock-hour maximum demands in each month has been adopted in a number of contracts as the billing demand. Furthermore, in cases of emergency, the large drafts of power following accidents or abnormal and unforeseen increases in traffic for short periods of time are usually furnished by the utilities, if they have the capacity available, without increasing the billing demand.

(*d*). A provision is included which requires that each monthly billing demand shall not be less than a specified percentage of any previous billing demand.—This supplements the requirements of (*a*) and (*b*) and takes into account the special characteristics of the railway's fluctuation in business from year to year. Except for some of the urban lines this fluctuation is very large, and if the railways were to pay for a high percentage of any previous demand when the traffic has shrunk considerably, their income would be diminished when vitally needed. For this reason they prefer that the unit demand charge be figured high enough to compensate the utility fully during the term of the contract, and that the guaranteed percentage of any previous billing demand which determines the yearly payment for "demand charge", be made more proportional to the amount of maximum load taken during each year.

(*e*). The practice as to whether the railway or the utility should furnish and operate the machines required to deliver direct or single-phase current is not uniform.—In the case of railroads electrified during the last few years the tendency has been to have the utility furnish, house, and operate such apparatus and supply energy directly to the trolley or transmission lines. In such cases provisions are made in the contract price for a proper compensation to cover the operating costs, conversion losses, and fixed charges including amortization. Clauses are also included for transferring ownership to the railway in the event of termination of the contract, at a sale price proportionate to the unamortized investment.

(*f*). The utility, in establishing these differences in the terms of various contracts, carefully analyzes the effect of each variation and accordingly provides price differentials which will avoid discrimination among customers. The general clause on reduction of rate if more favorable rates are given other customers also protects each purchaser in respect to these special provisions.

Underlying Economic Factors

The utilities are justified in making the foregoing departures from their standard forms of power contracts in the case of electrified railways, since experience has shown that this valuable business could not be secured without giving the underlying economic factors full consideration from the standpoints of both the railways and the utilities. We have already made occasional references to these factors but it is also important to explain more comprehensively how they affect the two industries.

Load Factor

In general the utilities have a much higher use of their maximum demand than the railways which means that they are able to render more service per kilowatt of plant capacity. This is caused by the great variety of their customers and the resulting time diversity of maximum demand and use of the service. Furthermore, although the railway's load factor is, in general, less favorable than the utility's, when the two loads are superimposed with their diversity in time of respective maximum demand, the combined load factor is improved and conditions are created for realizing substantial economies in plant investment. These investment economies are, of course, further enhanced by a saving in the amount of spare capacity which would be required if the railway were to install and operate an independent generating system for the lines to be electrified. Similar economies may also be realized in connection with the power transmission system. Therefore, if the railway electrification loads are supplied by a heavily-interconnected utility industry these factors will produce economic results to the advantage of both the railways and the utilities.

Rate of Growth

The utilities with their continuous growth in load, in contrast with the more or less stationary load of a railroad for a given situation, are in a better position to continue to improve their operating economies, as they have done in the past.

These economies were realized in part from the fact that the quantities of power handled by the electric utilities became so large that it was possible for them to install generating and transmission units of large capacity with correspondingly lowered unit costs, reduced operating labor costs, and improved efficiencies. At the same time, the utilities were enabled to produce the major portion of their power requirements from their newer and more efficient units, by operating them at high load factors and gradually relegating their older plant to usage for peak or standby service.

For illustration, the graph, figure 1, gives the distribution of capacity and output according to the date of installation of units for a large system during the year 1934. It shows that of the total capacity, the 20 per cent installed before 1919 was used to give less than 2 per cent of the total output and the 50 per cent installed before 1926 was used to give less than 28 per cent of the total output while the other 50 per cent installed between 1926 and 1934 and incorporating the latest advancements in the art as to the size and efficiency of machines, higher steam pressure, higher steam temperature, more efficient boilers,

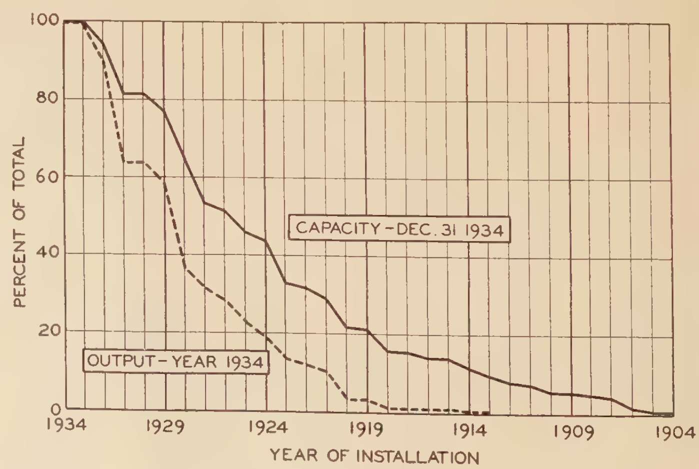

Figure 1. Total generating capacity installed in or prior to indicated year compared with energy generated by corresponding units during the year 1934

and all other station improvements generated 72 per cent of the total output. This progress in securing higher economies is a continuous one as long as the industry is growing.

Sources of Power

In contrast with the foregoing favorable situation of the utilities in supplying power, it is evident that large-scale electrifications under present-day conditions, if served with power by the railways themselves would either require several suitably located and relatively small power plants, which necessarily would involve high unit investment and operating costs, or alternatively would require excessive investment in transmission facilities in order to distribute over a widespread area from some centrally located plant. In either case a relatively high amount of reserve capacity would be needed to insure the reliability of the service. The advantageous position of the electric utilities with their large and economical plants at many load centers, and large-capacity transmission facilities generally available at other load centers not directly served by generating plants, is obvious.

Status of Electrification

Notwithstanding the fact that steam railroads have had the possibility of using electric traction available to them for many years, they have not found it feasible to utilize this form of power except for the few special cases to which we have referred. The reason for this has been stated to be the large new investment which would be required. It would be appropriate to add practical illustrations of the net results of operation before and after electrification, taking account of the changes in capital investments and all other factors affecting the net results. Unfortunately most of the comparisons available to the public deal in generalities or apply only to a specific phase of the subject. Furthermore, any comparison would be entirely dependent on the circumstances of the case, and would vary widely between different roads, or divisions of the same road, depending on traffic, profile, speed, and many other conditions.

Comprehensive data on the results of electrification have been published for the Chicago, Milwaukee, and St. Paul Railroad, and a recent analytical study of all the factors affecting the total net results of the Italian Railways may be found in Mr. Carli's report to the 1938 World Power Conference on "Comparative Results of Operations of Italian Steam and Electric Railways for the Year 1936–37" (*Elettrotecnica*, April 25, 1939). From the latter we can draw the conclusion that, apart from other important advantages *unrelated to the operating costs*, their savings by the use of electric traction are mainly due to the high cost of coal in Italy and would disappear entirely if their cost of coal were the same as in the United States. These conclusions are arrived at by a comparative analysis of Mr. Carli's tabulation, for the steam and electric systems, of all expense items that relate to the supply of power and operation of the transportation department, including interest charges on investment in locomotives and power equipment.

The aggregate expense per ton mile of steam traction was 17 per cent higher than for electric traction. Unfortunately Mr. Carli's study compares steam traction with electric under great differences in density of traffic; the electric lines with only one-third the mileage of the steam lines, carried $17^1/_2$ billion ton miles against $21^1/_2$ billion ton miles carried by the steam lines. This fact greatly favors the electric-traction system, and seriously limits the absolute value of the comparisons, although the relative value of the conclusions reached above are not disturbed. In analyzing the items of expense we find that the cost of coal was of the order of $8.70 per short ton. The equivalent cost for the class I railroads in this country was about $2.43, this low average price being partly due to the Interstate Commerce Commission accounting system which excludes from fuel expenses any cost or charges for its transportation on the reporting company's lines. But even if a liberal allowance were made for such charges, the American price per ton of fuel would have been less than one-half that of the Italian Railways. If the price in Italy had been on the same relative basis as in America the excess cost of steam traction would have been eliminated entirely.

The electric lines handled the 17.5 billion ton miles with an average consumption of 43 watt-hours per ton mile or a total of 750 million kilowatt-hours. Of this total the railways generated about one-fourth in four hydroelectric stations owned by the State, and purchased three-fourths from the utilities at 42 high-voltage delivery points. These results give a practical confirmation of the conclusions reached under the heading of "Underlying Economic Factors" and emphasize the fact that such economies are secured jointly with an infinitely greater insurance of continuity of service which is provided, not only by the large number of high-voltage delivery points, but also by the numerous generating plants back of them, which insure the supply of the utilities under abnormal conditions of operation.

Future Possibilities

Up to 1937 the railways in the United States had only electrified to the extent of consuming 1,627 million kilowatt-hours, which is estimated to be less than $2^1/_2$ per cent of the total business. This would indicate that, under present conditions and prevailing prices of coal, electricity has not demonstrated definite advantages over steam traction except in a very few special cases where other considerations unrelated to operating costs might have influenced the change or where heavy traffic conditions and relatively high operating speeds prevail. We need considerably more analytical information to clarify the problem as to why the largest industry in this country has not adopted electric traction more widely. For the present, therefore, it is impossible to make any sound forecast of its probable growth. We must, however, bear in mind that changes in this country are apt to be rapid and powerful and that the utilities may eventually find in the railways a field for steadily expanding their power sales. The theoretical demand for such services, if all the railways were to be electrified would be of the order of three-fourths the present output of the entire central-station industry in the country. Only a third of this potential total would be as large as the present consumption of all residential consumers.

There are many obstacles in the way of further electrification which are not related to the cost of electric power but, to the extent that this cost influences the whole problem, the utilities have demonstrated that the railways can buy electricity from them more advantageously than they can secure it in an alternative way. In securing this business the utilities would be benefiting all their customers, because the economies realized from service to the railways ultimately accrue to the advantage of all users of electricity.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Overcurrent Performance of Bushing-Type Current Transformers

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Synopsis: Conventional methods used for defining and comparing current-transformer performances are commonly based on their ratio and phase-angle characteristics. For years, these characteristics have been continuously improved, particularly with respect to the requirements for metering service. However, from the standpoint of circuit protection, current-transformer application becomes more involved and as a result, increased attention has been given it.

A better knowledge of transformer performance is necessitated by the requirements of new relays and protective schemes. Attention to the influence of the d-c component in short-circuit transients is especially necessary when using high-speed relays. Also, in differential connections, the necessity for equivalent matching of saturation characteristics is essential. These are illustrations of the types of problems which ratio and phase-angle characteristics alone do not solve. The analysis of open-circuit saturation curves has proved of immense value in the solution of these problems.

This paper gives results of investigations on bushing-type transformers that indicate the proper choice of analysis procedure and the limitations of the various methods for determining performance under overcurrent operating conditions.

THE PURPOSE of this paper is to present the results of an investigation on the scope and limitations of saturation and loss curves in the application of bushing current transformers to relaying problems involving the overcurrent performance. The investigation covered the method of taking such data, the methods of calculation and the accuracy of ratio and phase-angle performance as calculated from it, and the application of the data to simplification of relaying problems.

The use of voltage-saturation and watt-loss data to analyze the performance of magnetic circuits has always afforded a means of predetermining the performance of devices associated with such circuits. Generators, transformers, and similar devices have their basis of design on these known characteristics of the magnetic material used. This leads to simplicity of investigation for a given set of conditions, and provides information which otherwise could be obtained only with the conditions peculiar to the investigation.

Within certain limitations it should be possible to formulate a practical analysis of the overcurrent performance of bushing-type current transformers in terms of the induced voltage and associated losses in a specified magnetic circuit independent of the operating conditions. The latter would be specified in terms of ratio, secondary burden, and primary-current range. These characteristics, if given in a desirable form, should be as suitable to the application engineer as they have been to the design engineer, and should find a wide range of usefulness.

Transformer Performance Characteristics

The conventional method for defining and comparing the performance of current transformers has been their ratio and phase-angle characteristics. Considerable information has been published relative to the improvement of these characteristics, particularly over the ranges of load currents and burdens encountered in metering service. These characteristics, particularly ratio, have been extended to cover the higher ranges encountered in relaying service.

With the advent of new relays and protective schemes the application of current transformers has become more involved, and the use of the conventional performance data has often proved inadequate for successful solution of certain types of these problems. Recently much progress has been made in application of high-speed relays[2,3] with the attending problem of transient performance by the use of open-circuit saturation curves. Many have found this criterion of great benefit in the solution of problems involving the overcurrent performance of bushing-type current transformers.

Saturation and Loss Data and Vector Diagram

A theoretical consideration of the vector diagram of the current transformer figure 1, which is the same as that for the conventional voltage transformer, shows that in general the primary constants of resistance and leakage reactance do not influence the performance, except by virtue of the indirect influence of the primary upon the secondary leakage reactance.[1] The difficulty of separating these leakage reactances is well known, and any effective use of the open-circuit saturation curve for calculating performance requires a knowledge of the approximate value of this reactance. For through-type current transformers with a ring-type core, symmetrically spaced, distributed secondary winding, and reasonably spaced primary conductor, the secondary leakage for low and medium core densities is sufficiently small that it can be neglected.[1,4] The usual bushing-type current transformer fits these requirements and hence the open-circuit saturation curve and equivalent circuit should lend themselves to the simplification of many problems involving the knowledge of its performance.

Method of Measuring Excitation Characteristics

Of the numerous methods of obtaining saturation and loss data on current transformers, the direct measurement of these quantities on the secondary winding with the primary open-circuited has been chosen for its simplicity, flexibility, and economy. It has been found when making such measurements that the wave shapes of the currents and voltages, and the types of measuring instruments used have a direct bearing on the results. Previous experience indicated satisfactory calculations of transformer performance could be made from saturation and loss data taken by impressing sine wave voltages and measuring the rms voltages and currents.

As it is often difficult to determine and maintain wave form when obtaining saturation and loss data, tests were made to determine the influence of wave shape. A 600/5 multiratio bushing current transformer for a 138-kv oil circuit breaker was tested; first, using sine-wave impressed voltage, and second, circulating sine-wave exciting current. As illustrated by figure 2, both voltage and current are essentially sine wave for core densities below saturation, while either one or the other, or both, must be distorted when the core becomes saturated. The results obtained throughout the complete range of core densities are shown in figure 3. These curves also indicate, when using sine-wave

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2. For all numbered references, see list at end of paper.

Figure 1. Typical vector diagram of current transformer

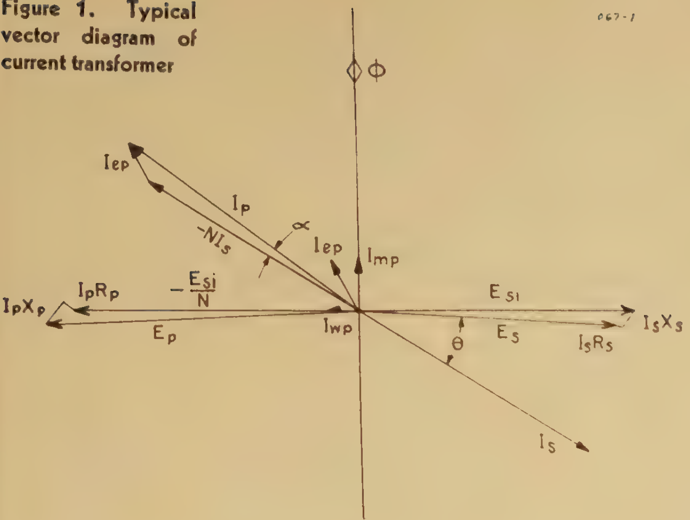
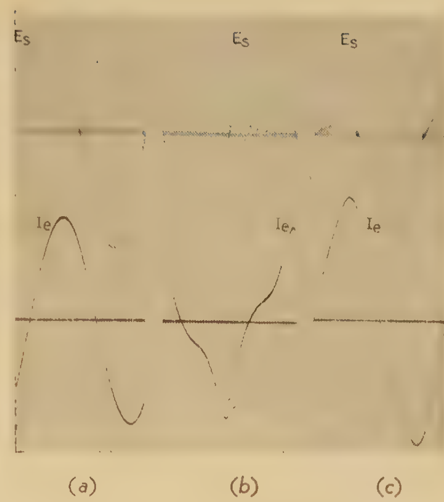


Figure 2. Typical oscillograms of current-transformer saturation characteristics

(a)—Sine-wave voltage and current—medium flux density

(b)—Sine-wave voltage—saturated density

(c)—Sine-wave current—saturated density



exciting current, the difference in results from measuring the voltage with a repulsion-iron voltmeter which reads rms voltage, and the Rectox voltmeter which reads the average voltage multiplied by the form factor 1.11.

It will be noted that there is quite close agreement between the sine-wave voltage and sine-wave current excitation curves, when the voltage, in the latter case, is measured with a Rectox voltmeter. This is in accordance with accepted practice, as it is known, that for a distorted voltage wave having the same average value as a given sine wave voltage, the maximum flux is equal. The equal values of maximum flux represent equivalent flux conditions independent of wave shape.

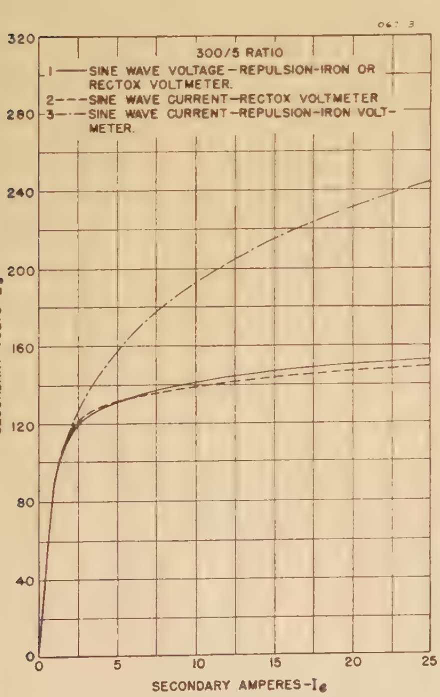


Figure 3. Saturation characteristic curves taken at sine-wave voltage, and at sine-wave current

Under operating conditions the primary current of the transformer is essentially a sine wave. Through the lower-density range the exciting currents, secondary induced voltages, and burden currents are all approximately sine waves. In the saturated region all of these quantities are somewhat distorted. However, the errors introduced by these harmonics are relatively unimportant unless they are large, and then only when the total exciting current is an appreciable portion of the primary current. These conditions are illustrated by the oscillograms of figures 4*a*, *b*, and *c*.

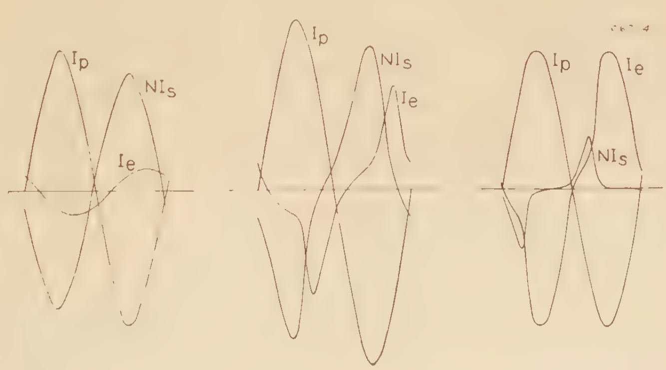
It appears from a practical operating viewpoint that saturation tests may be made independent of wave form when using rms ammeters and voltmeters responding substantially to average voltage but with an rms sine-wave calibration. Such data will give sufficient accuracy for most performance calculations.

Effects of Primary and Secondary Winding Locations on Performance

In an effort to determine the effect of and variations in the secondary leakage reactance of bushing transformers at high values of overload currents, conventional ratio and phase-angle tests were made on several oil-circuit-breaker transformers. The standard multiratio transformer has the total secondary winding well distributed over the core, but the various lower ratios are obtained by means of tapping portions of the secondary winding, resulting in relatively poorer distribution on the low and intermediate ratios.

From a theoretical viewpoint the variation of secondary leakage with the position of secondary winding is increased with closer proximity of the primary return conductor, with higher magnitudes of primary current, with greater asymmetry of the secondary winding, and with increased core diameters. In this investigation the transformers were tested with the approximate spacing of the primary conductor as encountered in practice, and with two different positions of secondary winding with respect to the primary return as shown by positions *AA* and *BB* of figure 9. Position *AA* represents the middle axis of the secondary winding in a relation to the return conductor which gives the condition of mini-

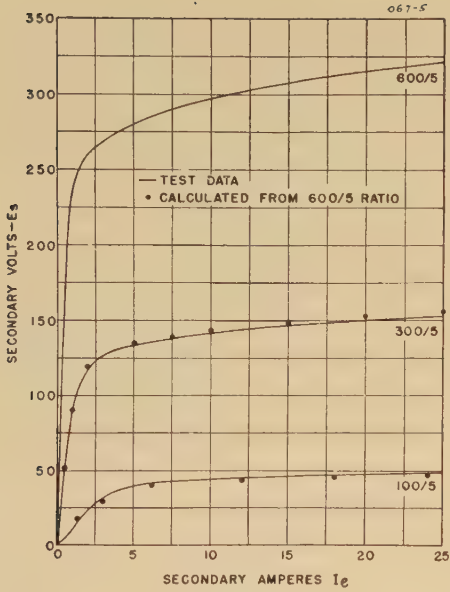
Figure 4. Reproduced oscillograms showing wave shape of primary, secondary, and resultant exciting currents with a secondary burden of 50 volt-amperes, 100 per cent power factor



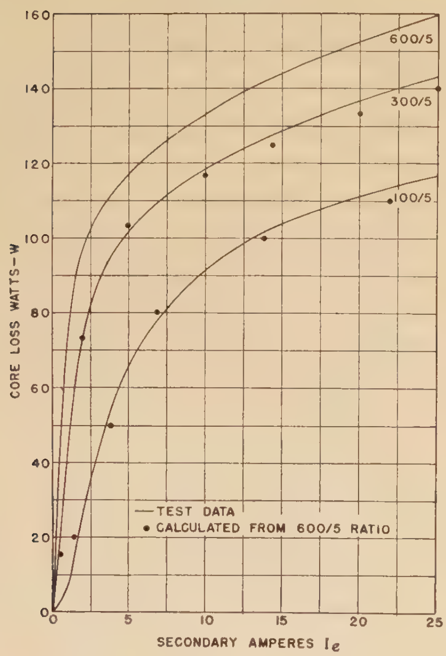
(a)—Medium flux density

(b)—High flux density

(c)—Saturated flux density



(a)



(b)

Figure 5 (left). Saturation and watt loss characteristics of a current transformer

(*a*)—Voltage versus exciting current

(*b*)—Watt loss versus exciting current

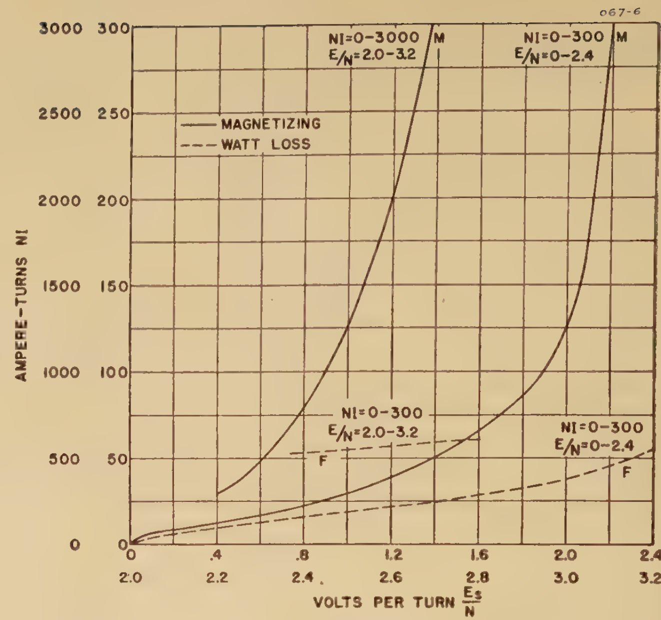


Figure 6. Ampere-turn versus volt-per-turn characteristics of bushing current transformer of figure 5

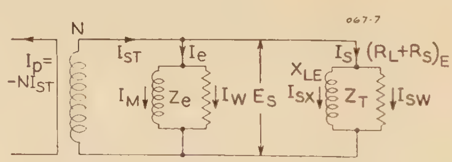
mum coupling, and likewise position *BB* gives a maximum coupling.

These tests, typical results of which are shown by figures 9*a*, *b*, and *c* are not sufficient in scope to establish definite boundaries for all of the parameters previously listed. However, for standard bushing current transformers with core dimensions and return conductor spacings encountered in conventional apparatus, and for primary currents up to 25,000 or 30,000 amperes, satisfactory results in calculations involving relay applications can be obtained when the secondary leakage reactance is neglected. This is particularly true when it is observed that most of such applications use performance data based on nonsaturating burden impedances, which is, at times, coarsely modified to meet actual operating conditions.

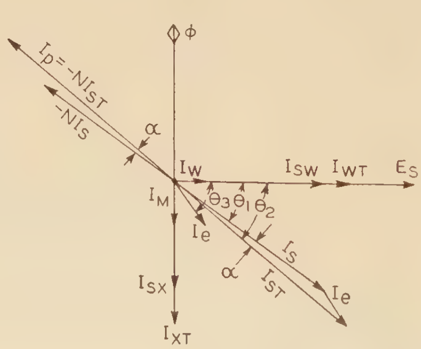
Various Forms of Saturation and Loss Curves

The saturation and loss data taken under the conditions previously outlined result in a set of data as shown in figures 5*a* and *b* for various ratios. The data thus taken can be shown in several different forms, and may be converted into similar data for any other ratio using the same magnetic core. Two forms are indicated by the curves of figures 5 and 6, and the methods which can be used for these conversions are given in appendix II. The first form gives voltage and watt loss versus exciting current in secondary terms for a given ratio, while the second form gives the core loss and magnetizing components on an ampere-turn versus volts per turn basis which is independent of the ratio.

Attention is directed to the curves in figure 5, where the full-line curves are plotted test data, while the indicated points on the 100/5 and 300/5 ratios are conversions from the 600/5 data using equations 10, 12, and 13 of appendix II. These curves indicate that very satisfactory transformations from one ratio



(a)

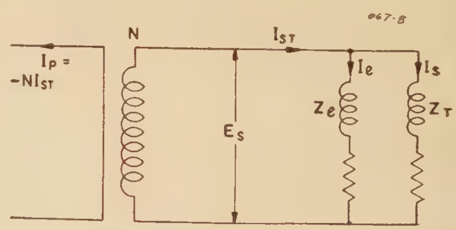


(b)

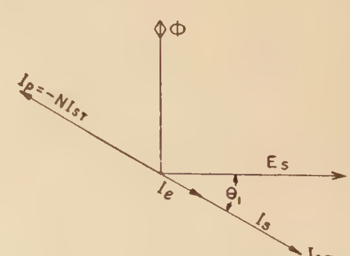
Figure 7

(*a*)—Equivalent circuit of current transformer on secondary base

(*b*)—Vector diagram of (*a*)



(a)



(b)

Figure 8

(*a*)—Simplified equivalent circuit of current transformer on secondary base

(*b*)—Vector diagram of (*a*)

to another may be made, the greatest source of variation coming from the use of commercial rather than precision testing facilities. Figure 6 is another form of expressing the data as calculated by equations 4 to 8 of appendix II. In this form they may be considered the master curves since they give the fundamental data which can be used to calculate the saturation and loss curves, and other calculations based on these data for any ratio using the same core. Since bushing current transformers have only the single primary turn, the ordinates for the magnetizing and loss ampere turns of figure 6 could be conveniently called primary amperes.

Calculation of Ratio and Phase-Angle Performance

The formulas for the calculation of transformer performance from the saturation and loss curves are given in appendix III. These calculations may be divided into two classes; the first giving both ratio and phase angle, and the second giving approximate ratio. In this connection it is interesting to note the theoretical effect of burden power factor on the phase-angle error of the transformer, as illustrated by figure 7. For lagging burdens the maximum possible phase angle error for any degree of saturation is less than 90 degrees and decreases with decreasing burden power factor, but in practice seldom exceeds 30 or 40 degrees. With unity or leading power factor burdens the phase-angle error may approach 90 degrees. Hence, for burdens having very lagging power factors the second method of calculation gives good results.

The agreement between the first method of calculation and test data is indicated in figures 9a, b, and c which show the comparison between calculated and actual test performance. As indicated, there is a difference between the results which occur for the following reasons:

1. Neglect of secondary leakage reactance which has been previously mentioned.

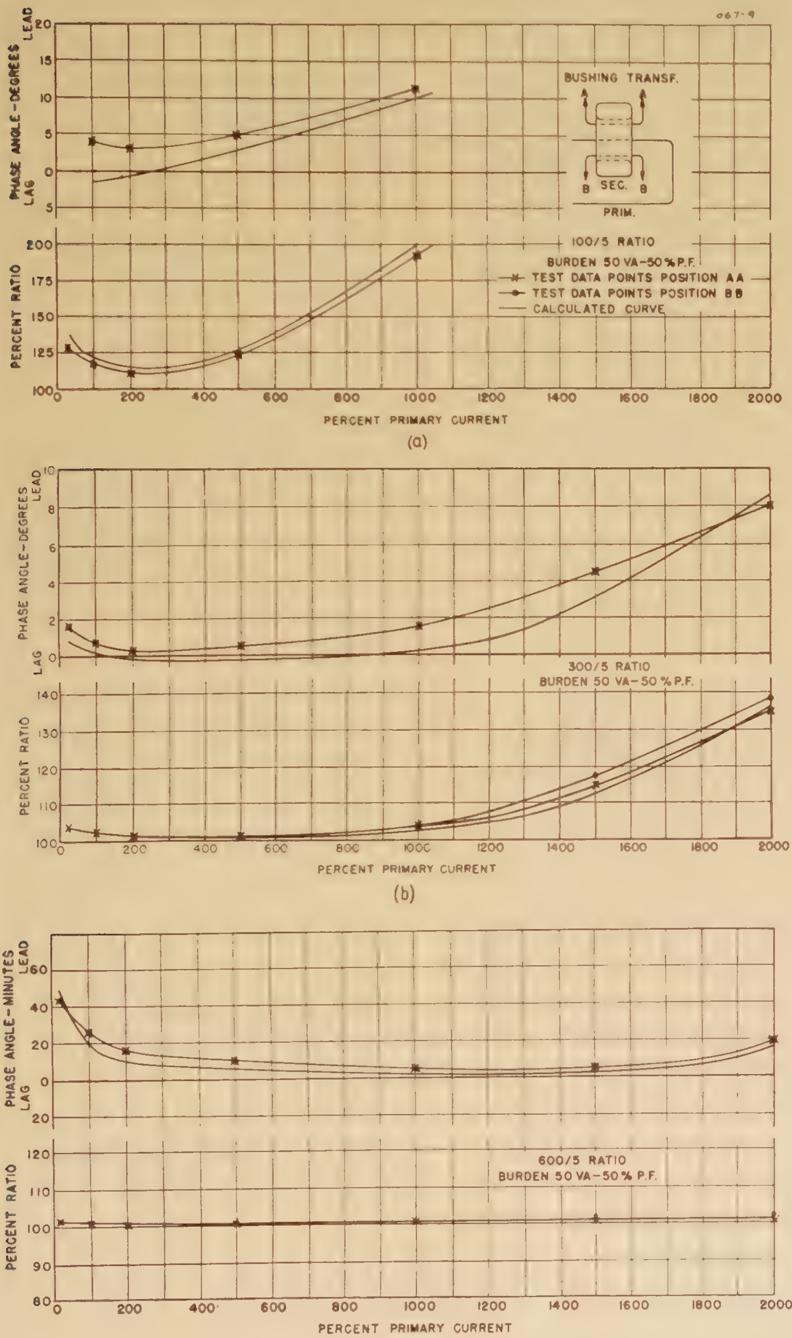


Figure 9 (left). Ratio and phase-angle calculated and test characteristic curves of current transformer

(a)—For 100-to-5 ratio

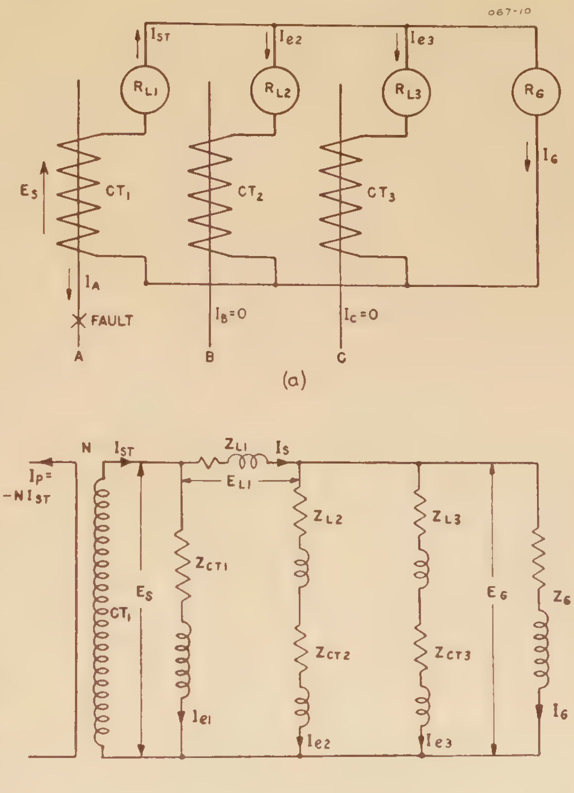
(b)—For 300-to-5 ratio

(c)—For 600-to-5 ratio

Figure 10

(a)—Typical three-phase relay circuit

(b)—Equivalent circuit for (a)



2. Neglect of harmonics, particularly with respect to their effect on the phase-angle error. The null test method used to obtain the phase angle compares the fundamental-frequency components of the secondary and primary currents, while the method of calculation has assumed all quantities are of fundamental frequency.

3. The order of accuracy of test data, including both saturation and loss data, as well as ratio and phase-angle data. Test errors could be reduced to a minimum by increasing the precision of the testing facilities. However, the work described herein was done with ordinary commercial testing equipment in order to observe the limitations which might be imposed on the use of saturation and loss data in practical applications.

Application to Relay Problems

In a large number of applications it is only necessary to determine if the degree of linearity of the transformer performance with a given burden over a specific range of primary current is within required limits. A glance at a saturation curve such as shown in figure 5*a* enables one to estimate quickly the limits over which approximately linear performance will be obtained. This can be defined as the maximum voltage obtainable with any permissible value of exciting current which may be expressed on a percentage basis, such as two per cent, five per cent, or ten per cent of the total primary current on the secondary base. If with this value of exciting current the secondary voltage developed is equal to or greater than necessary, then the transformer will meet the requirements. The procedure for this form of calculation is outlined in appendix III, part *c*.

In a simple three-phase circuit with overcurrent or directional overcurrent relays, ratio curves can be readily used to determine the relay settings for phase faults. With the addition of ground relays and faults involving ground the problem of division of the total secondary current into the several parallel branches of the circuit is encountered as shown by figure 10. If the transformer ratios are high (high impedance) the current which leaks through the parallel circuits may be neglected with little error, but when relatively low ratios are involved this problem often becomes quite serious, resulting with incorrect relay operation. The saturation curve lends itself admirably to the solutions of problems of this nature as outlined in appendix IV. It will be evident that additional refinements can be made on this method by taking into account the vector relationships and all of the circuit constants. Again, in cases involving the paralleling of transformers of two or more circuits, similar problems of leakage of the secondary current through the multiple circuits and the effective burdens are encountered.

Conclusions

From the foregoing it is evident that the open-circuit a-c saturation and loss data will be extremely useful in the field of relay application. It can be utilized to determine relay settings for various magnitudes of secondary burdens and primary currents, as well as ratio and phase-angle characteristics. The data may also be used to determine the range of linear performance, which is valuable in any application, and is particularly useful in comparing characteristics of transformers for differential protection schemes. Where a knowledge of the exciting impedance is required for the determination of leakage currents in branch circuits, it may be easily obtained from the saturation and loss curves. This information, like that required for transient performance, cannot be readily obtained from the conventional performance curves.

When the saturation and loss data are available on any ratio they can be used to determine the performance on any other ratio using the same core. Likewise, they can be used for any burden within the capacity of the transformer; the latter when defined in terms of permissible error and current range, is quite evident from such data. This is not the case with ratio curves where the application engineer, in the field, often is seriously handicapped in the solution of his problems by the lack of ratio data on the desired ratio, burden, or range of primary current. Since the versatility of the saturation and loss curves lends itself to the simplification of many diversified problems, they should appeal as a means of more clearly defining the overcurrent characteristics of bushing-type current transformers.

Appendix I—Glossary

E_{si}—Secondary induced internal voltage—secondary base
E_{si}/N—Secondary induced internal voltage—primary base
E_p—Primary terminal voltage
E_s—Secondary terminal voltage
E_s/N—Volts per turn
E_{sk}—Secondary voltage of transformer at a specified exciting current
I_sX_s—Secondary leakage reactance drop
I_pX_p—Primary leakage reactance drop
I_sR_s—Secondary winding resistance drop
I_pR_p—Primary winding resistance drop
I_s—Secondary burden current
I_{ek}—Permissible value of excitation current for a secondary voltage E_{sk}
NI_{ST}—Total secondary current—primary base
NI_S—Secondary burden current—primary base
I_{ep}—Core excitation current—primary base
I_{wp}—Core excitation watt component of current—primary base
I_{mp}—Core excitation wattless component of current—primary base
I_p—Primary current
I_e—Secondary excitation current
I_W—Watt component excitation current
I_M—Wattless component excitation current
I_{ST}—Total equivalent secondary current
I_{SX}—Equivalent wattless component burden current I_S
I_{SW}—Equivalent watt component burden current I_S
I_{XT}—Total equivalent secondary wattless current
I_{WT}—Total equivalent secondary watt current
X_{LE}—Equivalent secondary burden reactance
$(R_L+R_S)_E$—Equivalent secondary burden resistance
R_L—Burden resistance
R_S—Secondary winding resistance
F—Watt component of ampere turns
M—Wattless component of ampere turns
T_n—Times normal voltage or current
α—Primary-secondary current phase angle
θ—Burden power-factor angle
θ_1—Equivalent secondary power-factor angle
θ_2—Angle between E_s and I_{ST}
θ_3—Excitation current angle
ϕ—Core flux
N—Transformer secondary turns
W—Core loss watts
NI—Ampere turns—primary or secondary base
Z_T—Total secondary burden impedance
Z_B—Secondary burden impedance
Z_e—Open-circuit transformer impedance
R_{L1}, R_{L2}, R_{L3}, R_G—Line and ground relays
CT_1, CT_2, CT_3—Bushing current transformers
I_A, I_B, I_C—Line currents of a three-phase system
Z_{L1}, Z_{L2}, Z_{L3}—Impedance of line relays
Z_G—Impedance of ground relay
I_G—Ground-relay operating current
E_G—Relay voltage at I_G current

Appendix II—Forms of Saturation and Loss Curves

Saturation and loss test data as shown in figure 5, may be presented in several forms, all based on the ampere-turn excitation required for a given induction in any particular magnetic circuit. These data have been taken with open-circuit primary, reading the impressed voltage and watts loss at specified values of secondary circulated current. The induced voltage is taken equal to the impressed voltage, since the resistance drop of the winding is of small magnitude and becomes negligible when considered in its vector relation to the impressed voltage. The watt loss of the secondary winding is ap-

preciable in comparison to the core loss and the observed data has been corrected to take this into account. Hence:

$$E_{si}=E_s \tag{1}$$

At a given voltage E_s for N turns, the exciting current is I_e, figure 5a, and the exciting volt-amperes are:

$$E_sI_e \tag{2}$$

At this current I_e the core loss is W watts, figure 5b. The angle between E_s and I_e as shown by figure 7b is θ_3 and is expressed:

$$\theta_3=\cos^{-1}\frac{W}{E_sI_e} \tag{3}$$

The exciting current is divided into its magnetizing and loss components I_M and I_W respectively:

$$I_M=I_e\sin\theta_3 \tag{4}$$

$$I_W=I_e\cos\theta_3 \tag{5}$$

The data may then be interpreted in values independent of the secondary winding.

$$\text{Induction}=\frac{E_s}{N}\text{ volts per turn} \tag{6}$$

$$\text{Excitation}=NI\text{ ampere turns} \tag{7}$$

The excitation in ampere turns is the same on either primary or secondary turn basis, and since the bushing transformer has only one primary turn it follows that:

$$I_{mp}=NI_M=M$$

and

$$I_{wp}=NI_W=F \tag{8}$$

By the use of equations 4 to 8 a set of data for a given ratio and core as represented by figure 5a and b may be converted into the general form as given by the curves in figure 6.

Another convenient form of interpreting these test data as obtained on one ratio N_1 to another ratio N_2 is shown by the curves for the 100 to 5 and 300 to 5 ratios in figures 5a and b; and is derived on the following basis:

For a given voltage E_{s1} and loss W_1 on turn basis N_1 with exciting I_{e1}:

$$N_1I_{e1}=N_2I_{e2} \tag{9}$$

Therefore:

$$I_{e2}=\frac{N_1}{N_2}I_{e1} \tag{10}$$

Likewise the induced voltage per turn:

$$\frac{E_{s1}}{N_1}=\frac{E_{s2}}{N_2} \tag{11}$$

Therefore:

$$E_{s2}=\frac{N_2}{N_1}E_{s1} \tag{12}$$

and

$$W_2=W_1 \tag{13}$$

By the use of equations 10, 12, and 13 the curves for the 100-to-5 and 300-to-5 ratios as shown by the indicated points in figures 5a and b are calculated and the agreement with test values is well illustrated.

Appendix III—Calculation of Performance Characteristics

(a) Ratio and Phase Angle

The calculations are based on the equivalent circuit and diagram figure 7, which refers all quantities to the secondary side and includes consideration of the vector relationships. Assume a burden Z_B at a power-factor angle θ, current I_S, and ratio N. The total burden Z_T includes the secondary winding resistance R_S. Hence:

$$Z_T=(R_B+R_S)+jX_B \tag{14}$$

$$\theta_1=\cos^{-1}\frac{R_B+R_S}{Z_T} \tag{15}$$

Also the secondary voltage required:

$$E_s=I_SZ_T \tag{16}$$

For this voltage the excitation current I_e is required and obtained from the saturation and loss curves. These currents are then separated into their watt and wattless components, and added vectorially as indicated in the equivalent circuit and vector diagram of figure 7, with the following equations:

$$I_{SW}=I_S\cos\theta_1 \tag{17}$$

$$I_{SX}=I_S\sin\theta_1 \tag{18}$$

The values for I_W and I_M are obtained from the curves of figure 6 for the induction E_s/N.

Therefore:

$$I_W=\frac{F\text{ (from figure 6)}}{N} \tag{19}$$

$$=I_e\cos\theta_3\text{ (from figure 5}a\text{)}$$

and

$$I_M=\frac{M\text{ (from figure 6)}}{N} \tag{20}$$

$$=I_e\sin\theta_3\text{ (from figure 5}a\text{)}$$

$$I_{WT}=I_{SW}+I_W \tag{21}$$

$$I_{XT}=I_{SX}+I_M \tag{22}$$

$$I_{ST}=\sqrt{I_{WT}^2+I_{XT}^2} \tag{23}$$

$$I_p=NI_{ST} \tag{24}$$

$$\text{Per cent ratio}=\frac{I_p(100)}{I_SN} \tag{25}$$

Substituting (24) in (25) and collecting terms:

$$\text{Per cent ratio}=\frac{I_{ST}(100)}{I_S} \tag{26}$$

$$\text{Per cent primary current}=\frac{I_p(100)}{\text{Rated primary current}} \tag{27}$$

Phase angle is:

$$\alpha=\theta_2-\theta_1 \tag{28}$$

$$\text{where }\theta_2=\tan^{-1}\frac{I_{XT}}{I_{WT}} \tag{29}$$

and θ_1 is given by equation 15.

(b) Simplified Method

The calculations are based on the equivalent circuit and diagram, figure 8, and assume all quantities to be scalar values in phase with the secondary current. These quantities are referred to the secondary side. The justification for this method is based on the fact that relaying burdens usually have low power-factor angles approaching the excitation angle. Thus the calculated results will indicate poorer ratio performance than obtained in service, and will disregard the phase-angle performance. Under these conditions:

$$E_s=I_SZ_T \tag{30}$$

where Z_T is obtained from equation 14.

The total secondary current is:

$$I_{ST}=I_S+I_e \tag{31}$$

where I_e is a value of exciting current obtained from a saturation curve similar to figure 5 for a given ratio N at voltage E_s. The primary current, per cent ratio, and per cent primary current are than obtained by equations 24, 26, and 27 respectively.

(c) Linear Performance Range

The determination of the linear performance range of a current transformer may be ascertained from a saturation curve by assuming an allowable percentage P of maximum primary current I_p for the core excitation current I_{ek}. The exciting current on the secondary base becomes

$$I_{ek}=\frac{I_p}{N}\times\frac{P}{100} \tag{32}$$

The value of voltage on the saturation curve corresponding to the current I_e for a given ratio N, yields a developed voltage E_{sk}. Comparing the burden voltage E_s at rated secondary current with the value E_{sk} indicates the number of times normal T_n, that the transformer will function linearly, or

$$T_n=\frac{E_{sk}}{E_s} \tag{33}$$

With I_p taken as the maximum primary current and $5N$ as the normal primary-current rating, then if, $T_n>I_p/5N$, the transformer provides linear performance over the considered range. If $T_n<I_p/5N$, this indicates that the ratio error is greater than the permissible assumed value P per cent and requires recalculation on basis of lower primary current.

Appendix IV—Application of Saturation Curve to Typical Relay Problem

A typical problem involves the relay protection of a three-phase circuit with grounded neutral using phase and ground-current relays as shown in figure 10. Assume line-to-ground fault current in phase A, and no current in phases B and C, then

the equivalent circuit for the three-phase circuit is as shown in figure 10*b*. Current transformers CT_2 and CT_3 in series with their respective line relays form leakage-current paths in parallel with the ground relay which may appreciably reduce the current I_G in the relay.

Assume the ground relay tap setting requires an operating current I_G, and following the practice outlined in appendix III, part *b*, wherein all quantities were considered scalar and in phase, the following procedure may be used to determine the approximate value of primary current required to operate the relay.

$$E_G = I_G Z_G \tag{34}$$

Since Z_{L2} and Z_{L3} are usually small compared to the transformer impedance, they may be neglected thus avoiding the complication of using a cut-and-try method to determine the total value of $(Z_{L3}+Z_{CT3})$. The result of neglecting the impedance of these relays will be in favor of the ground relay.

$$I_{e2} = I_{e3} \tag{35}$$

These values may be obtained from a saturation curve such as shown in figure 5*a* for the voltage E_G on a ratio N.

$$I_S = I_G + 2I_{e2} \tag{36}$$

$$E_{L1} = I_S Z_{L1} \tag{37}$$

$$E_s = E_{L1} + E_G \tag{38}$$

It then follows that the required excitation current I_{e1} for CT_1 may be obtained as previously noted for voltage E_s.

Then

$$I_{ST} = I_S + I_{e1} \tag{39}$$

and

$$I_p = NI_{ST} \tag{40}$$

This last equation gives the approximate primary current required to obtain the ground relay current I_G.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Power Supply for Railroad Electrification and Fundamentals of Power Contracts

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THE PURPOSE of this paper is to indicate and clarify the status of the American railroad as a major factor in the generation and use of power, the extent to which steam-railroad electrification has become an element therein, the effect of electric-power costs on the extension of railroad electrification, and the desirable features of power contracts in connection with such electrification.

Railroads as Producers and Users of Power

Before the advent of the electric street and interurban railway and the use of electricity for domestic and industrial lighting and power purposes, the railroads of the country were the large producers and users of power, of course developed in many relatively small steam-locomotive units. That power business has grown until in 1937 the aggregate indicated horsepower of locomotives in service on the 136 class I railroads (roads with operating revenues of more than $1,000,000 a year) amounted in round figures to 100,000,000 horsepower. This compares with an aggregate installed capacity of all utility plants—hydro and steam—of approximately 50,000,000 horsepower.

Extent of Railroad Electrification

There are approximately 250,000 miles of railroads in the United States of which 235,000 miles are in the class I group. Of this total only 1.3 per cent have been electrified (6 per cent in the rest of the world). This, however, represents a considerable mileage, namely 2,965 route miles (6,950 miles of track) distributed over 24 railroads. The main reason for this relatively slow progress is the high capital cost of electrification because of which operating savings do not result in a sufficiently quick payout to virtually compel electrification.

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Advantages of Electrification

Electrification permits operating accomplishments that are not possible with steam power; it increases the capacity of a given railroad thus frequently saving large expenditure for additional trackage or terminal facilities; it adds to the attractiveness of the service and the comfort of the public; and through operating savings usually more than pays fixed charges. Thus it is conspicuous in being a type of railroad betterment that provides many desirable facilities and at the same time "pays its way." Among the outstanding operating benefits are great reliability of operation, high degree of availability and serviceability of the traction units, and the almost unlimited amount of power that may be made available for the movement of traffic. Underground terminals and connecting tunnels would be impracticable without electrification and capacity limitations of long mountain tunnels are overcome thereby.

Today probably the greatest demand on transportation is for service and the above advantages, together with the high operating speeds attainable, make electrification a valuable factor in enabling railroads to meet this requirement.

Operating Savings Due to Electrification

The major elements of operating cost, wherein savings by electric power as compared with steam are effected, include:

Locomotive repairs. These are considerably lower under electric operation and constitute one of the largest items of saving. Enginehouse expenses, inspection, etc., may be included in this general group and in these substantial savings are effected.

Transportation costs enter into the picture—these savings are substantial when the improved operation with electric power can be fully realized and the service can be rendered with a smaller number of larger train units.

Miscellaneous and indirect savings usually aggregate a substantial sum.

Cost of electric power versus locomotive fuel is an important item. Under some conditions this cost makes the project unattractive and becomes a controlling consideration from the standpoint of operating costs and savings.

Advances in the Art

The major advances in the art of power production as affecting efficiency and cost have been in the conversion of the heat energy in fuel into mechanical energy, where the efficiency has always been relatively low. The efficiency of conversion of mechanical into electrical energy is already high and little improvement has occurred or can be expected here.

During the period of great improvement in boilers, furnaces, and prime movers due to more efficient combustion methods, higher pressures, and superheat and other advances in the design of steam-electric generating plants parallel progress has been made in the efficiency of the steam locomotive. Thus in the past 15 or 20 years, there has been a reduction of about 25 per cent in the coal consumption on steam railroads per transportation unit. In the same period, as shown by the Federal Power Commission's statistics, there has been a reduction of nearly 50 per cent in coal burned per kilowatt-hour in steam-electric power plants of the utility companies. These figures indicate that in so far as efficiency of conversion of fuel into mechanical energy is concerned, the stationary plant still has the advantage.

Public-Utility Supply Versus Railroad Generating Plants

In the early days of railroad electrification, including that of terminals and certain city transit lines, it was found economical or necessary for the railroads to build their own power plants. The characteristics of the supply—frequency, phase, amount and fluctuating character of loads, etc.—and the rates quoted by utilities for such supply indicated in many cases that substantial savings would result from the railroad building its own plant. An important part of this advantage is that the railroad plant is built to produce the kind of electric power required without conversion from 60 cycles and it can be conveniently located with respect to the railroad's load center. Latterly, some of these plants have been leased or otherwise taken over by the utilities and purchased-power contracts substituted for railroad generation. In connection with most of the larger and more important railroad electrifications, power in whole or in part is now purchased from the utility companies.

Characteristics of Railroad Load

All railroads, both in the United States and abroad, use for traction purposes current of other characteristics than 60 cycles three phase that now is the general standard in this country for commercial power systems. This means that converting equipment of some kind is necessary to produce either direct current or 25-cycle single-phase current required for railroad operation. Development of the static converter type of equipment for frequency changing may result in increased efficiency of conversion and ultimately in lower cost of such equipment.

On the shorter railroad electrifications, such as for terminal operation or for mountain-grade lines, because of heavy train units and other operating conditions the demand on the supply system fluctuates widely. In some cases also the peak loads frequently occur at irregular and unpredictable times. These, together with the characteristics of the current, are adverse conditions which tend to make the supply by the utility of such requirements somewhat difficult and relatively costly.

On the other hand, where the railroad electrification is extensive and the traffic dense and comprised of a large number of train units, the fluctuations are not unduly severe and the load factor is relatively high; also the heavy demands frequently occur at off-peak times with reference to the utilities' commercial load. These features are favorable and should tend to reduce the cost of supplying energy.

Supply From Several Utilities

On extensive electrifications where the electrified lines cover hundreds of miles of route and cut across territory normally served by a number of different utilities, it is usually necessary for the railroad either to choose between such utilities and provide its own transmission lines in addition to substations and trolley system or to enter into agreements with two or more of the utilities. In the latter case, the railroad's entire requirements must be covered and the rates should be so applied that the railroad pays on the basis of its system load factor; otherwise it will be penalized in regard to load factor due to dissimilar conditions in the different areas traversed.

In this connection it is interesting to note the effect the extension of electrification has had on the load factor which in turn affects the over-all cost of energy as illustrated by table I.

This table shows, as is well understood, that the load factor of the supply to purely suburban electrified lines is low because of the heavy morning and evening travel and relatively light load at other times of the day.

When this suburban service is supplemented by through passenger traffic or by both passenger and freight, there is a substantial improvement in load factor. When the through passenger and freight traffic becomes so extensive and heavy as to form the major portion of the load an excellent load factor results. Thus in the table the average monthly load factor gradually increased from 33 per cent for suburban traffic only to 62 per cent after the entire program of suburban and through electrification was carried out. If there had been no suburban electrification the average load factor due to through passenger and freight service would have been of the order of 75.

If the electrification had been divided into say three main sections the load factor for each section would have been lower and the sum of the peak loads or demands on which separate billings would be based would be of the order of eight to nine per cent higher than the actual system peak loads. This in the case above cited would have represented an additional power cost to the railroad of more than $200,000 a year.

The supply of power by several utilities at the railroad's system load factor can be made effective in either of two ways:

1. By the railroad installing transmission lines of sufficient capacity to interchange power and energy between the different areas, thus enabling each utility actually to deliver its share or quota of the total demand and energy requirements, through the railroad transmission lines, or,

2. By the utilities jointly contracting with the railroad and with each other to supply

Table I

Service Operated	Miles of Route Operated	Miles of Track Operated	Average Monthly Demand*	Load Factor (Per Cent)
Suburban only	130	400	37,000	33–34
Through passenger service added	180	600	60,000	46
Same, with through passenger service extended	350	1,200	76,000	48
Same, with through freight added	380	1,370	120,000	55
Same, with further extension of through passenger and freight service	675	2,190	141,500	62

* Based on three maximum clock hours per month.

the portion of the demand and energy actually drawn by the railroad in each area and combining or pooling the demand and energy and jointly billing the railroad.

Such utilities should be interconnected and operated in parallel on the 60-cycle side so as to maintain synchronism effectively and thus avoid momentary interruptions in the supply when trains pass from one area to another. Most of the utilities are already normally interconnected for their own operating and economic purposes and their lines often parallel important trunk lines of railroads in territory where the traffic is sufficiently heavy to warrant electrification. In some localities portions of the railroad right of way are utilized for transmission lines of the utility. Joint use of railroad electrification structures is also feasible in some cases.

It is desirable from the standpoint of cost of special equipment that the number of supply points should not be unduly multiplied. Broadly speaking, the power-supply system—railroad and utility—should be so planned as to involve the minimum total capital expenditure by the parties consistent with the requirements of the service.

In considering electric traction railroads are confronted with the high capital cost and are usually desirous of shifting to the utilities as much as possible of the cost of power-supplying equipment. Locomotives are at present usually purchased through equipment trusts, the money being borrowed at favorable interest rates largely independent of the credit status of the railroad. If a similar plan could be devised for financing the roadway power equipment at favorable rates, greater progress in railroad electrification might result.

Cost of Electric Energy

It is generally believed that a public utility engaged in generating and supplying electric power to all sorts of customers should be able to produce power at lower cost than can be done by a railroad in its own power plant or plants; also that utilities are willing to supply the railroads on the basis of actual cost, including a reasonable return on investment and, therefore, there should no longer be any question as to whether a railroad about to electrify should purchase its power or generate it. There are a number of considerations, however, that enter into this question and which have an important bearing upon the railroad's decision to buy power from the utilities on such cost basis. Amongst these are the rates covering fixed charges on capital investment which the utilities may find necessary to use in arriving at cost and which may for a number of reasons be relatively high.

Such factors coupled with the railroad's ability to generate in its own plant, conveniently located, the form of energy required to operate its trains, may in certain cases more than offset the lower cost to the utility of generating its standard form of electrical energy and then converting it for railroad use.

The trend in the average cost per kilowatt-hour for purchased energy has been downward for the past ten years or more in respect to residential, commercial, and interurban and street-railway business. There was no definite downward trend in the cost of energy purchased for steam-railroad electrification until 1935 and since then the reduction appears to have been mainly due to improved load factor or some other special conditions rather than the lowering of rates.

Power Contracts

Experience has shown that power contracts as between railroads and electric utility companies in order to be generally satisfactory to the railroads should provide for the following railroad requirements:

(*a*). The contract should be for a long term—say 20 years with renewal options—so as to amortize on a low rate basis the cost of special equipment. A longer term than 20 years would be permissible if the rates for demand and energy are on a "cost" basis thus assuring to the railroad the benefits of advances in the art.

(*b*). The utility should preferably, although not necessarily, provide and own the special equipment and supply the power at the phase, frequency, and possibly the voltage required for railroad operation. This would minimize the investment by the railroad but fixed charges on same should be on a low basis comparable with rates applicable to the railroad's own capital expenditures.

(*c*). It is preferable to the railroad for the utility or group of utilities to supply power at a sufficient number of points in the electrified zone to take advantage of the utilities' networks to reduce investment costs by the railroad and at the same time further assure reliability of the supply.

(*d*). While the railroads would like to purchase power on a flat or sliding rate per kilowatt-hour, much as they purchase fuel, it has so far been impracticable to work out such a basis and separate demand and energy rates are customarily used.

(*e*). Demand charges should be on a monthly basis and should be established by averaging three or more clock-hour peak loads in the month. In selecting such peak hours, those caused by abnormal and emergency conditions should be excluded. System peaks rather than sectional peaks should be used in determining the maximum demand. When railroad peaks regularly occur at utility off peak times such as between 9:00 p.m. and 7:00 a.m., this should be reflected in a fair way in the demand rate.

(*f*). The energy charge should be based on the summation of meter readings at all points and is properly subject to correction for fluctuations in cost of fuel. The demand and energy charges may be on agreed rates or they may be based on the actual cost to the utilities within upset or over-all limits, the elements of such cost being defined, the rate used in billings in any yearly period being based on the actual cost for the preceding year.

(*g*). Where a substantial portion of energy is generated in hydroelectric plants of either the contracting utility or its affiliates and is furnished on a cost basis a suitable correction factor should be applied because of the high first cost and low operating cost of such plants.

(*h*). Power contracts should be as simple as possible as to form and should eliminate all unnecessary conditions and stipulations that might lead to misunderstandings and disputes. No guarantee as to load factor should be required of the railroad, nor should guarantees as to the minimum demand charge following a previously established maximum be required. While minimum loads of two-thirds or three-fourths of the previously established demands have been stipulated in some railroad contracts, it is preferable from the railroad's viewpoint to eliminate such clauses. Wide variations are inherent in the nature of the traffic on trunk-line railroads and are quite beyond the control of the management. They should be understood and recognized by the utility but should not appear in the contract.

In conclusion, the writer would express the hope that the downward trend in the cost of generating and distributing electric power will presently be reflected in the rates offered for railroad electrification and will be on a scale which will make the cost of power one of the major items of saving by electrification. It is also the hope that at the same time ways may be found materially to reduce the capital cost of electrification. If these things can be accomplished, important pending projects may be undertaken with every assurance of attractive financial as well as operating results. In that case, power companies operating in the vicinity of newly electrified railroad lines would be assured of large additional blocks of load, and the best interest of two important groups of public servants would be mutually advanced.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Transactions

Preprint of Technical Papers Comprising Pages 563–602 of the 1940 Volume

Restoration of Service on a Metropolitan Power System

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THE purpose of this paper is to outline procedures and discuss pertinent problems that arise when restoring service to a metropolitan system following a major shutdown. In the discussion, consideration is given to the fundamental plan of the system, pointing out the inherent features in the design which prevent such failures. Several cases of trouble which have been the cause of service curtailment have been discussed and the service restoration procedure outlined. A brief outline of the essential procedure is given for two types of service restoration.

The conclusions and procedures discussed in this paper are the result of experience gained from failures which have occurred on the Duquesne Light Company system. It is recognized that the resultant procedures and conclusions may not be applicable to other systems. However, this paper does discuss many conditions which are common to all systems and therefore this paper may be helpful in formulating a service restoration procedure.

Description of Facilities for Supplying Load Areas

The power sources of the Duquesne Light Company system are comprised of three steam generating stations and two medium-capacity interconnections. The Colfax power station, which is located 18 miles east of Pittsburgh on the Allegheny River, delivers its 262,500-kw capacity to the 66-kv transmission system. The Brunot Island and Reed power stations which are located 4 miles north of Pittsburgh on the Ohio River, have a total capacity of 236,500 kw; use a common switch house; and, in general, supply the 11-kv and 22-kv load for the downtown Pittsburgh area and the industrial section adjacent thereto. All the power stations are directly connected to the 66-kv transmission system which acts as a high-capacity tie between the generating stations.

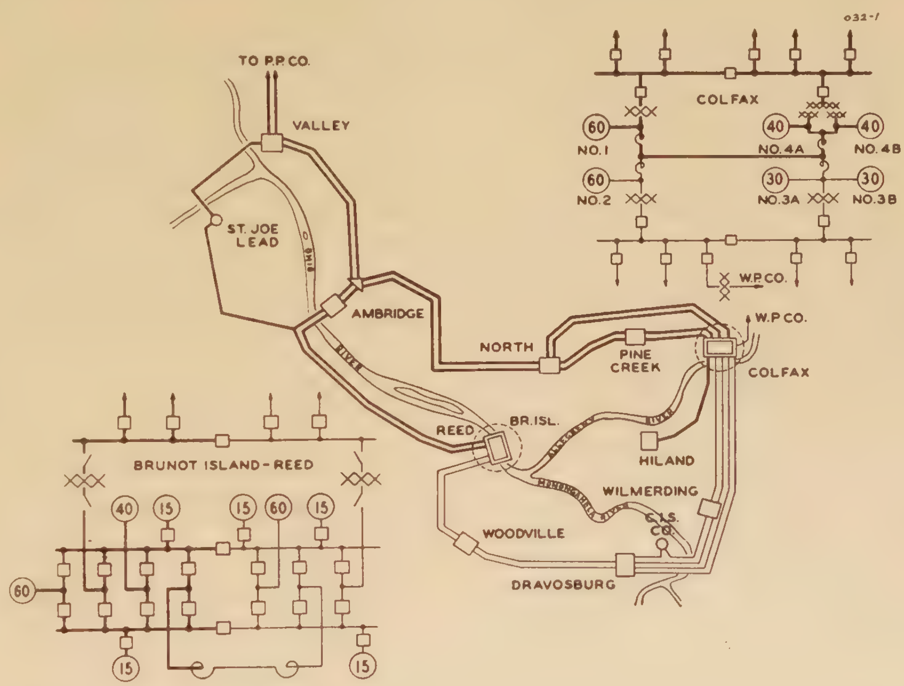

Figure 1. Schematic diagram of the Duquesne Light Company system

Inserts show schematic bus diagram of power stations

The 66-kv transmission system and the power stations normally have a running order that provides two segregated power systems which are referred to as the north and south rings. The 66-kv transmission system is essentially a ring surrounding the major part of the Pittsburgh territory having a secondary ring extending north and west along the Ohio River. This scheme provides a duplicate source to each of the substations located on the transmission ring. The sectionalizing of the system into a north ring and a south ring is accomplished by reactors between respective bus sections at the power stations (figure 1).

There are eight step-down substations on the transmission ring which feed definite load areas. In general, these stations feed isolated load blocks but are provided with secondary ties which are used for emergency power transfers. These substations are the source of the 22-kv feeds to the distribution stations supplying 4-kv service in the congested areas. They also supply the street railways and the high-voltage industrial service. In general, each one of these substations comprises a complete unit of the distribution system (figure 2).

The downtown Pittsburgh area and the industrial area adjacent to it are supplied from the Brunot Island switch house and are not directly dependent upon the 66-kv transmission ring. This area is supplied by a 4-kv radial system and a low-voltage network. The network system has four

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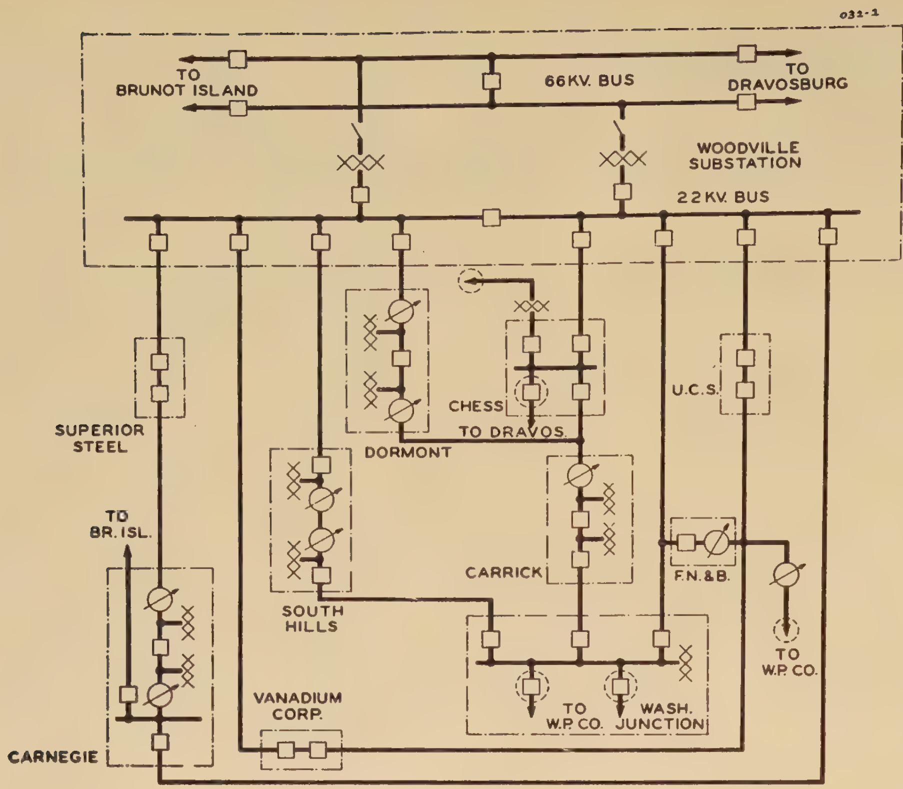


Figure 2. Schematic diagram of the Woodville 66-kv ring substation and related transmission circuits

separate areas, two areas having 4-kv feeders from downtown substations, and two areas fed at 11-kv from the Brunot Island switch house. Each 11-kv network area has its power source from bus sections operating on opposite sides of the ring. The feeds to these areas are further protected by connecting individual feeders to separate bus sections. The 11-kv cables which feed other services are connected to the Brunot Island bus in the same manner. The failure of a single bus section in the switch house, therefore, should not result in interruption of customers' service (figure 3).

In addition to the network load, the Brunot Island switch house is the source for various street-railway stations, and numerous high-voltage customers. The combined load in this 16-square-mile area reaches a maximum of 100,000 kw, 25 per cent of the system load. Due to the high load density in this area and the relatively short transmission distance, this service is supplied at the generator voltage.

The fundamental plan of the bulk power system involves its segregation into two main sections, commonly referred to as the north ring and the south ring. This provides ties between generating sources over two distinct and separate paths; and, due to the method of connecting the halves at the power sources through reactors, permits a fault to be immediately isolated with minimum effect on the remainder of the system. This plan reduces the probability of a major system shutdown due to transmission trouble. In the event of a ring split, the reactors in the power stations can be shunted out, thereby relieving the transformers of possible overloads.

A complete failure of a ring substation should only affect a limited area, although it may result in a ring split. The power requirements for these areas can be partially supplied by utilizing tie lines to adjacent areas, thus limiting the effect of a major substation failure. Transmission capacity is provided to cover the loss of one ring substation transformer bank.

The Brunot Island switch house is operated with two main bus sections, using the bus tie breakers to provide the emergency back up. Further protection is provided at the Brunot Island switch house by the isolated-phase construction.

Power-Station Auxiliaries

The layout of the auxiliary system follows, in general, the same plan as the transmission system. Two sources are supplied the duplicate equipments on each of the major generating or boiler units. One of these feeds usually has its source direct from the unit itself, while the remaining equipment has its source from other units or transformer banks connected to the opposite side of the transmission ring. Auxiliary power sources are provided by separate steam-driven station-service generators, station-service generators driven from the shafts of main units, or station-service transformer banks. This provides combinations consisting of either a house generator and a station-service transformer or station-service transformers supplied from opposite sides of the transmission ring. The separate voltage sources minimize the loss of auxiliaries due to disturbances on the transmission system. Station-service generators are available at the Brunot Island and Colfax power stations to assist in the initial start-up of these stations. The Brunot Island station-service generator, while not located in the Reed power station, is available for use at that location.

The major part of the station-service power supply is equipped with voltage-transfer devices which transfer the unit auxiliaries to a normal-voltage source in event of failure of the regular power supply. The voltage transfer eliminates the necessity of other types of reclosing. Simultaneous reclosing devices, provided to energize the auxiliary busses after a complete outage, do not appear advisable in many cases due to the characteristics of the auxiliary drives.

In addition to the general plan of sectionalizing all the main power sources into two sections, much effort has been expended in improving the bus construction and clearances, installing faster relays and circuit breakers, co-ordinating insulation, providing gas barriers and fire protection, and improving test and maintenance procedure, all with the intent to decrease the probability of failures.

With the ring substations responsible for the service of eight major load areas, and the Brunot Island switch house covering the requirements for downtown Pittsburgh and adjacent areas, the 66-kv breakers at the ring substations, or the 66-kv breakers at the power stations, have adequate capacity to restore these load areas.

The low-voltage network presents a somewhat different problem and a master control switch has been provided at Brunot Island to reclose simultaneously any combination of breakers feeding each of the network areas. This simultaneous reclosing of each network area prevents de-energizing sections of the Brunot Island switch house for the purpose of reclosing the network through a bus-tie breaker. The simultaneous-reclosing scheme was easily applied due to the use of spring-operated breakers which eliminated consideration of control difficulties

involved during simultaneous reclosure of solenoid-operated breaker mechanisms.

Major Operating Experiences

In discussing the operating experiences of the Duquesne Light Company which have involved an outage to a major section of the system, a brief outline of the type of loads served is necessary in order to visualize the response of the customers to service restoration.

The residential and commercial load, which is mainly lighting, is approximately 25 per cent of the total system load. The growth of refrigeration and air conditioning appear to be factors which will influence restoration of this service in certain areas. The industrial service, which comprises about 53% of the system load, includes much rotating equipment provided with low-voltage interlocks, the use of which prevents instantaneous pickup upon restoration of service. The remaining load is mainly street-railway service, which is supplied by synchronous converters or motor generator sets. This equipment is sensitive to system disturbances and generally requires manual restoration, except for a few unattended automatic stations. It is not unusual for a noticeable decrease in system load to occur following a severe voltage disturbance, due to the loss of synchronous equipment. It is believed that this condition is more favorable to rapid restoration of service than residential and commercial load, which approaches a resistance characteristic.

The major hazards which would involve a serious outage on the system fall into three classes:

1. *Electric Failures at Vulnerable Points on the System.* These involve failures either of bus sections in the power stations, transformer failures, or ring substation failures. These failures are the most frequent type of hazard, but, except for one or two cases which occurred many years ago, they have not caused other than a momentary disturbance to the system. The loss of one main generating unit is not considered a serious hazard as adequate spare capacity is normally available at all times.

2. *Loss of Transmission Facilities Due to Storms, Hurricane, or Sleet.* This condition would severely interfere with service but fortunately very little trouble has been experienced in the Pittsburgh district due to these causes. The geographical location precludes any great probability of a hurricane or tornado impairing the transmission system. The hazard from sleet is relatively great in this area. Severe sleet storms have not involved any important transmission circuits since 1925, although they have occurred frequently immediately adjacent to the Duquesne Light territory. Electrical storms are severe in this locality and have caused most of the major transmission failures.

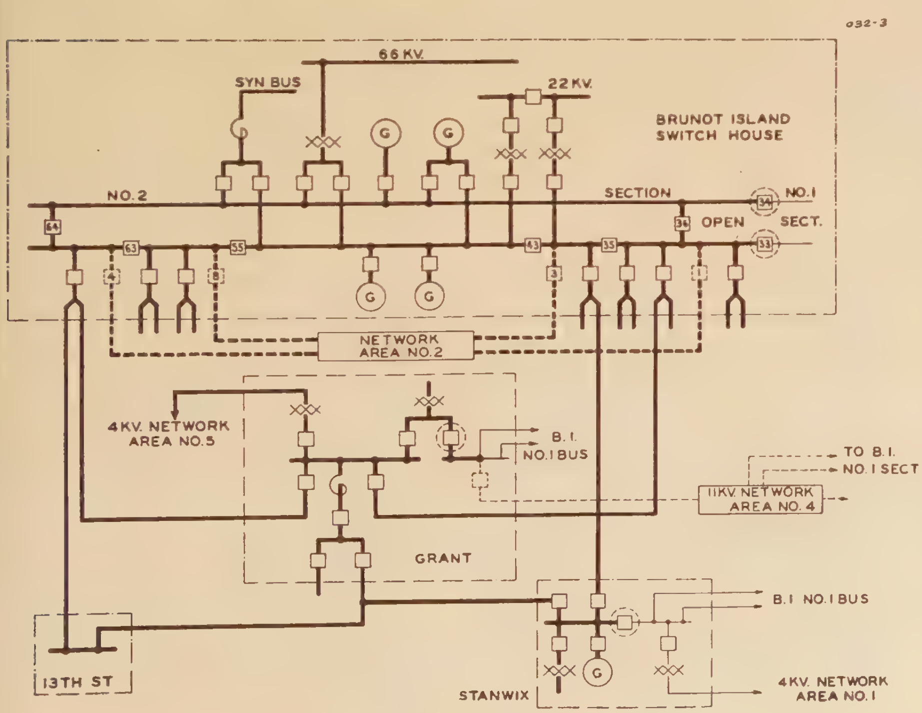
3. *The Flood Hazard.* The flood hazard has been recognized and the system facilities have been installed to provide continuous service beyond what appeared to be a record flood. However, in March 1936 the most severe flood in the history of Pittsburgh occurred and resulted in an almost complete shutdown of the system; all but 2,500 kw of the entire system load was dropped. In the Pittsburgh district a flood does not present any serious hazard to the main transmission system, although it does affect many parts of the system serving industrial customers and domestic customers. However, due to flood conditions, these customers could not utilize the service if available. The generating stations, being in the river valleys, are subjected to the full brunt of the flood wave.

The most severe outage the system has experienced, except in the flood, occurred on Sunday evening, September 25, 1927, at 7:17 p.m. as a result of instability. Extending over a period of 31 minutes following the start of this disturbance, severe hunting existed between power stations and between generating units within the power stations. In order to restore stability to the system it was necessary to sectionalize the system, each area being fed by a separate generating unit with the load so proportioned as to come within the unit's capacity. The switching incidental to this split up was performed during the instability and resulted in immediate recovery following its completion. This disturbance resulted from a combination of factors which involved operation of the system below the normal voltage level while transformer taps were being changed to raise the voltage level of the 66-kv transmission system. This resulted in lower generator voltages which, combined with an error in the load forecast as a result of the changeover from daylight saving time, resulted in the instability. It is not expected that this condition will occur again from these causes due to the rigid maintenance of generator voltages and the operation of adequate reserve capacity.

There have been within recent years two major disturbances resulting from transmission-line failures which have upset the normal distribution of load in the transmission ring. On both occasions the 66-kv transformers at Brunot Island were tripped by the overload relays, isolating more load on the station than could be carried.

One major outage due to a transmission failure occurred on July 3, 1929. The primary cause of this disturbance was the failure of a ground wire on a four-circuit river crossing between the Wilmerding and Dravosburg substations on the south ring, splitting the south ring. This operation interrupted the normal power flow through this section which supplied part of the south-ring substations and the south-ring feed to the Brunot Island 11-kv bus. The interruption caused the power flow to seek a path across the reactor bus at Colfax along the north ring, through the 66-kv transformers at Brunot

Figure 3. Schematic diagram of typical Brunot Island section and related transmission circuits



Island across the 12-kv reactor bus and out through other 66-kv banks to the remaining substations on the south ring.

This redistribution of load caused severe overloads on the transformers connected to the north ring at Colfax and Brunot Island. The overload relays on the Brunot Island transformers connected to the north 66-kv ring tripped this bank, leaving 130,000 kw of load isolated on the Brunot Island station with 100,000 kw of capacity operating at 50,000-kw load. Due to the inability of the station to carry the entire load the frequency dropped to 56 cycles, reducing the load to approximately 110,000 kw. In a short time the steam pressure dropped from 190 pounds to 145 pounds and the voltage dropped from 11,600 volts to 10,200 volts. As a result of the low steam pressure the Brunot Island output decreased to 92,000 kw, indicating that it was necessary to quickly drop part of the connected load at this station in order to prevent the steam pressure from reaching a level where the station would have to be completely shut down. This is particularly important at this station, due to steam-driven auxiliaries for the boiler room and turbine room. The 66-kv transformers to the south ring and the transformers feeding the 22-kv transmission system were opened, relieving the station of all but the local 11-kv and low-voltage network load. The frequency and voltage recovered to normal and the station load settled at 75,000 kw.

With the frequency back to normal the station was immediately paralleled with Colfax through the north 66-kv ring and the 22-kv and 66-kv transformers reclosed. There were no difficulties experienced in picking up the load which was a result of service restoration. The nearness of this disturbance to noon hour resulted in a smaller total load than existed previous to the disturbance. The possibility of a simultaneous failure of any four-circuit transmission line is considered to be so remote that no precautions are taken to provide for this contingency.

Another major disturbance due to a transmission failure occurred on August 13, 1935, at 9:11 a.m. This occurred at approximately the same relative location on the north ring as the south-ring disturbance just described and involved a double-circuit tower line. The conditions preceding this disturbance were abnormal, in that a 60,000-kw unit at the Reed power station was out of service for maintenance. Enough capacity was operating in the Brunot Island power station to protect against the loss of one of the 66-kv transformer banks, thereby providing backup for the Brunot Island local load. However, lightning struck this two-circuit transmission line and the resulting relay operations split the north 66-kv ring, routing the feed to the Valley district through the Brunot Island 12-kv bus and 66-kv transformers on the north ring.

Immediately preceding this disturbance the Brunot Island station output was 20,000 kw with 55,000 kw boiler capacity in service. The local Brunot Island bus load was 64,000 kw, 44,000 kw of which was being fed in through the 66-kv transformer banks. The sectionalizing of the north ring diverted about 40,000 kw additional through the south ring, which, added to the 44,000 kw required for the local 12-kv bus load, resulted in operation of the overcurrent relays on the south-ring 66-kv transformers. This isolated 104,000 kw of load on the same bus section with 55,000 kw of generating capacity operating at 20,000 kw. Under this tremendous overload the steam pressure dropped from 190 pounds to 100 pounds within one minute, and to 60 pounds within another half minute. A maximum load of 64,000 kw was observed on the Brunot Island station immediately after the stations had separated.

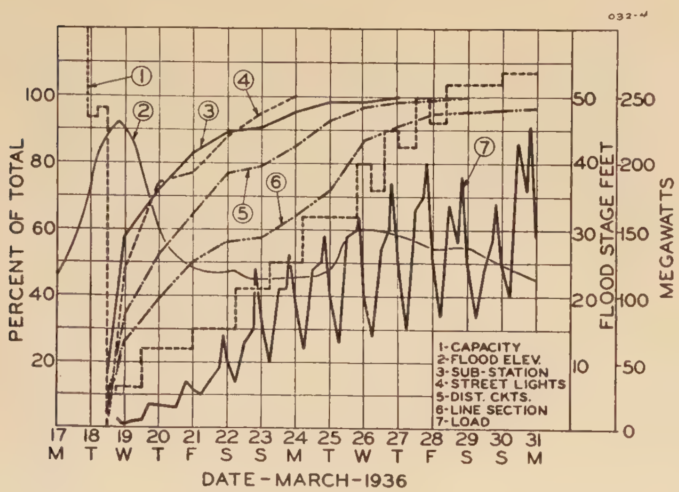


Figure 4. System condition following the 1936 flood

Immediately following the tripping of the south-ring transformer breaker at Brunot Island, the Brunot Island-Ambridge 66-kv lines were opened, relieving the generators at this plant of 40,000-kw load, in an attempt to restore the frequency in order to synchronize with Colfax. This load was immediately reclosed on the Colfax power station. After this relief, the Brunot Island generator load continued to decrease to 35,000 kw and then slowly decreased to about 22,000 kw, due to loss of steam pressure and failure of steam-driven auxiliaries. The frequency at this time was below 50 cycles, that being the lowest frequency scale observed and the bus voltage decreased from 11,600 to 7,500 volts. At this time, the Brunot Island 11-kv bus was de-energized and all generating equipment disconnected from the bus.

De-energizing the Brunot Island 11-kv bus resulted in a complete outage to the 23,000-kva low-voltage network load and all of the 11-kv and 22-kv transmission in the area adjacent to downtown Pittsburgh. Various 11-kv loads were sectionalized at Brunot Island during the disturbance and service was restored to the network and the remaining loads by energizing the 11-kv bus from Colfax through the north 66-kv ring transformers at Brunot Island. Preceding the restoration of network service, the Colfax power station load was 137,500 kw. Immediately upon re-energizing the Brunot Island station, which involved only the low-voltage network and a few 11-kv services, the Colfax load increased 56,500 kw to 194,000 kw. In the intervening period the remaining circuits, which had been sectionalized in an effort to relieve the Brunot Island load, were reclosed. By 9:42 a.m. the Colfax station load had increased to 252,000 kw. During this interval the generators at Brunot Island were synchronized on the system and brought up to 29,000-kw load.

At one interval shortly after service had been restored the station operators reported a total system load of approximately 282,000 kw between the usual 15-minute reading interval. This peak existed for approximately 5 minutes and was thought at the time to have resulted from the loss of diversity in refrigeration and elevator loads due to the extended period of the outage and some excess load due to simultaneous re-establishment of

service by the high-voltage industrial customers.

These two cases of trouble involved a complete outage to relatively large blocks of load and yet in both cases when service was re-established there was no evidence that the generating equipment was unable safely to handle the load.

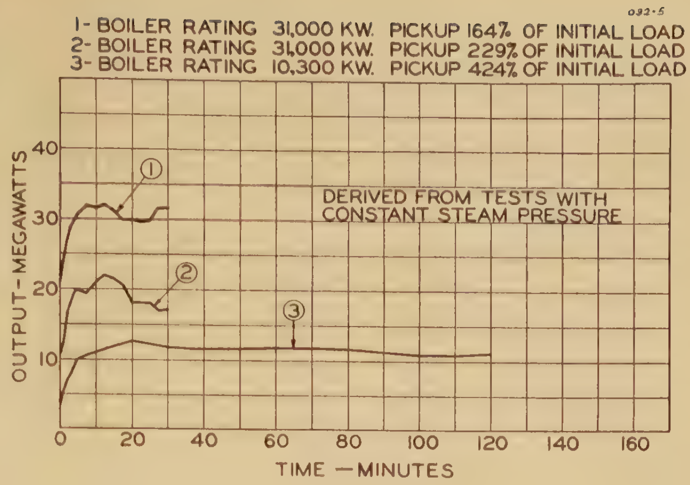
Since this last disturbance, generation and spare capacity has been allocated to the several load areas in such a manner that not only is the system protected for loss of generating capacity but each major load area is protected against loss of either generator or transmission capacity, except in the case of four-circuit tripouts.

There have been two other recent major electric failures which involved bus sections at the Colfax power station. In one case a 60,000-kw unit was completely crippled, due to a three-phase short circuit which destroyed an entire 12-kv bus section. The unit operating setup prevented these failures from interfering with the operation of the balance of the station, except for the voltage disturbances during the fault.

The most serious outage the system has ever observed started on March 18, 1936, as a result of the all-time record flood on the Allegheny and Monongahela Rivers. The flood stage reached a maximum elevation of 46.2 feet which was 36.2 feet above the normal river level. The highest previous flood, since the settlement in Pittsburgh, occurred, in March 1907, at which time the flood reached a level of 39.7 feet. Serious trouble was first encountered at a 39-foot stage about 4:00 a.m. on March 18. Preceding this time a few transmission and distribution circuits had been lost and most of the high-voltage customer stations in the low-lying industrial districts had been taken out of service at the customers' requests. Shortly after this flood water began to involve major substations and equipment. In rapid succession the 66-kv north-ring transformers at Brunot Island; the 11-kv control board at the Stanwix substation which feeds part of the downtown Pittsburgh district; and all system transmission and distribution services on Neville Island and adjacent districts along the Ohio River were removed from service. During this period the communication circuits were failing. By early morning contacts had been lost with many substations, the Brunot Island and Reed power stations, and the dispatching headquarters for the downtown distribution division and the substation division.

The operating problem during this period consisted of isolating faulted equipment and maintaining what service was

Figure 5. Typical stoker boiler response curves—constant steam pressure



possible on the remaining lines. About 7:00 a.m. the flood had reached the circuit-breaker mechanisms of the 66-kv line breakers at Colfax power station and the 66-kv and 22-kv line breakers at Brunot Island, making it impossible to operate any of the outdoor switching equipment and crippling the protective-relay system. However, this equipment was not removed from service due to failure of the control. When necessary, switching was done manually from boats. The system load reached its peak Wednesday at about 8:00 a.m. and decreased steadily after that time due to the flooding of customers' equipment. The loss of load on the system due to the effects of the flood reduced the system demand below the available capacity of the generating stations so that up until the time of shutdown there was adequate power for all essential services that were outside of the flooded areas.

Although the low-voltage-network areas in downtown Pittsburgh were practically all flooded, service was available until the system shut down. The submarine-type equipment withstood the flood with an insignificant amount of damage.

The Brunot Island station was the first generating station to abandon operation. The Reed power station was taken out of service at 11:20 a.m. due to flooding of the electric-bay basement. The turbine room was not flooded.

The Colfax power station continued to operate until 3:50 p.m. although a leak in the foundation which was adjacent to a field rheostat required removing from service a 40,000-kw unit at 11:37 a.m. This leak and some minor damage to the electrical equipment was repaired and the unit was about ready to return to service when it was necessary to shut down the entire station.

It was known for some time previous that there was little chance of averting a general shutdown. The 66-kv transmission system had been sectionalized so that the opening of a single breaker would drop a block of load. By this means the shutdown could be accomplished in an orderly manner without undue risk to the equipment at Colfax. It was also thought best to drop the load by opening a single beaker in order to forestall damage to customers' equipment which might result if operated at low voltage and frequency. The authorization to shut down was given at 3:47 p.m. following a rupture in one of the foundation walls in the Colfax power station. The dropping of sectionalized load areas proceeded and as the Colfax station load was reduced a generating unit was disconnected from the system by opening the main transformer breakers.

The first unit was off the line at 3:50 p.m., three minutes after the shutdown authorization was given and the last unit was off the line at 3:58 p.m., 11 minutes after the initial order. The station-service generators had been flooded by water entering the air ducts and were not available for some time preceding the shutdown. The total system load dropped was approximately 110,000 kw. This procedure was executed in remarkable fast time without any operating errors or any other event which in any way damaged any of the generating equipment or exposed the operating personnel to undue risk. All main equipment was de-energized before the flood water reached the insulation.

At this time several 22-kv transmission lines, which had previously been transferred to adjacent power companies, were carrying a load of approximately 2,500 kw, which saved the system from a complete shutdown.

The problem facing the operating organization at this time involved complete de-energizing of all the substation control

equipment in order to conserve station service batteries until such time as the transmission system could be again energized.

With the generating stations shut down, the only possible way of restoring a few of the most essential services rested on the availability of the interconnections with other utilities. The need for station service at the power stations was of prime importance to permit immediate re-establishment of dewatering operations. While arrangements with other utilities were being made for power supply, attention was given to organizing the dispatching facilities of the substation and distribution departments. These dispatchers were moved to offices adjacent to the system operator to eliminate telephone congestion. These moves did not retard the rehabilitation work as no action could be taken until the flood waters had receded about ten feet. In the meantime the management formulated a "service priority list" to designate the order by which service was to be re-established. The list follows:

1. Communication

(a). Police and fire signal systems
(b). Telephone communication, including telegraph

2. Essential service, including cities, towns, and townships

(a). Water pumping
(b). Hospital service
(c). Dairies
(d). Bakeries

3. Street service

(a). Municipal street lighting
(b). Street cars (curtailed service only)

4. Newspapers
5. Domestic electric lighting
6. Commercial light and power
7. Industrial

Startup From System Shutdown

Before discussing any plans or sequence of starting up a system, it should be recognized that the cause of shutdown necessarily dictates the method of re-establishing service. With this thought in mind, two types of shutdowns will be discussed. The first case will have particular reference to the flood failure, which, briefly, is a type where total generating capacity is curtailed and cannot be immediately restored. A second case is assumed whereby some unforeseen electrical failure causes a complete shutdown, with the power sources, transmission system, and substations immediately available for service re-establishment upon isolation of the faulty equipment.

The system was shut down in an orderly manner in spite of the communication difficulties. This was due in part to instructions to all substations not to attempt reclosure in event of circuit failures and also to open and clear all circuits in event of loss of power supply. Prior to shutdown, arrangement was made with a local radio station to broadcast switching instructions to the Colfax power station, in the event of complete telephone failure, but these arrangements were not used.

First consideration was given to establishing station service to the Colfax power station. This was accomplished at 6:33 p.m. by use of a 22-kv interconnection with the West Penn Power Company to the Dravosburg substation. This station then energized Colfax through a 66-kv line and one of the main transformer banks. These banks were without their water-cooling facilities and were operated intermittently to prevent overheating.

The 66-kv interconnection with the Pennsylvania Power Company at Valley substation was energized next at 8:04 p.m. and Colfax transferred to this source. The West Penn Power Company tie was unavailable due to flooding of both the Colfax and Springdale switchyards.

Due to the flooding of the 11-kv cable potheads at the Brunot Island switch house, service could not be restored at this station until the cable terminals could be replaced, although a source of feed was available. The cable operation was complicated by the flooding of the 11-kv grounding-bank connections. The Brunot Island plant was completely flooded so that normal service facilities could not be used to dewater the plant.

The next major step was restoration of the Bell Telephone facilities in the downtown area served from the 11-kv network. This customer had a multiple-unit vault, one cable of which originated at Grant, and energizing the network feeder, all network transformers were stripped from the network feeder and the street main fuses opened at the Bell vault. The pickup of this service cannot be overemphasized, as its effect was immeasurable in insuring communication channels both for civic and company use.

On March 19, 1936, all load that had been restored was carried by the 66-kv interconnection at Valley and numerous 22-kv interconnections with the West Penn Power Company, each source serving isolated load blocks. At approximately 9:30 a.m. on this date, many substation busses and transmission lines were energized to facilitate service restoration to water-pumping stations, and other essential loads, most of which were served at 11 kv or 22 kv. At 12:15 p.m. additional capacity was added to the system by closing the Colfax-Springdale tie line to the West Penn Power Company. All load at this time was confined entirely to essentials, and the total system output limited to about 40,000 kw. In order to limit the service pickup to the priority list, a gigantic task was being performed by the distribution department in stripping the necessary circuits of non-essential load in order to limit the output to the interconnected capacity available.

On March 20, service was broadened to include some residential load, mostly rural, for the re-establishment of water supply. A total of about 30,000 kw was added in this manner, bringing the system output to about 74,000 kw.

Meanwhile, the power stations department was working to restore generating capacity, but was handicapped in many ways. At Brunot Island, for instance, the station was badly flooded and had to be dewatered. To accomplish this, a flood pump had to be moved in by a crane which required 500-volt d-c service. As the rotary converters at the Brunot Island station were inundated, service to the crane could not be established until a rotary converter was made available. By the time this was accomplished station service was available from the switch house through temporary leads.

The Reed power station, after drying out the coal-handling and circulating-pump equipment, was restored to service. It was necessary, however, to inspect and clean all the electrical connections in the Brunot Island switch house before power could be utilized from this unit. The boiler plant at Reed was kept on a live bank during the entire period, by permitting the coal reserve in the bunkers to drop to the floor and manually firing through the end doors, utilizing natural draft. The boilers supplied steam for a boiler feed pump which was temporarily modified to pump the seepage from the turbine room basement.

To fully appreciate the problem at Colfax, requires a brief description of the plant at the period immediately following shutdown. The flood water, while not affecting the turbines or generators, completely inundated the turbine-room basement crippling the main-unit auxiliaries entirely. In the switchyard, water had reached the 66-kv breaker mechanisms for the 66-kv lines and the West Penn Power Company tie line and had damaged practically all control cable.

At the time of the flood a 30,000-kw unit was being overhauled. All the auxiliary equipment below flood level that could be removed was moved above flood

level thereby providing enough motors on another 30,000-kw unit to replace the flooded equipment. This made it possible to start the first 30,000-kw unit at 4:10 a.m. on March 22 about 84 hours after the shutdown.

In contrast to the other plants, Colfax had station service shortly after the shutdown. The boiler plant was completely down, and the first stoker-fired boiler placed in service about $39^1/_2$ hours after shutdown.

At 5:15 p.m., March 23, the Reed number 1 unit was returned to service, increasing the system capacity. At this time the scope of pickup was expanded to include all available residential load. All distribution circuits outside of the flood area were cut in, and part of the load which had been stripped from circuits was restored. The pickup for this day amounted to about 50,000 kw.

The estimated demand at this point was about 20,000 kw in excess of capacity. This condition was set up to improve the load factor and with the intent of dropping any excess load over the peak period. During this period emergency overload ratings were in effect on all operating equipment.

The addition of generating capacity to the system required special relay settings and bus setups to protect adequately the equipment involved. These setups were too numerous to mention, but it is important to note that all equipment energized had some sort of protection provided. The system at this time was still segregated into several isolated load blocks with the largest block carried by the Duquesne Light Company stations. All of the available interconnections were still in use.

The load pickup was made along well-defined lines. As generating capacity was made available, a program was devised to bring the system peak load up to the available capacity. This was accomplished by preparing an hour-by-hour forecast of system load for the next day. As the system proper was still isolated into load areas, the load to be added was tabulated under the area affected and a total determined for the forecast. The aggregate of the areas gave a forecast for the system which was surprisingly accurate. Since the essential loads available were already connected, the forecast program assisted in determining the amount of excess power available in an area that could be prorated to the next succeeding service class on the priority list. On March 24 and 25 many industrial customers were reconnected on a restricted basis. As the generator capacity was increased, the isolated load blocks fed by various interconnections were transferred back to normal and by March 26, all services connected were on an unrestricted basis. At this date, however, there were many customers without service in the flooded areas.

After energizing the 11-kv bus at Brunot Island, the testing and energizing of the low-voltage network began. The transformers were cleared on all 11-kv feeders and the feeders tested individually from Brunot Island. With the feeders out, all transformer units unaffected by the flood were closed and the feeders closed at Brunot Island on a dead bus. The bus and network were then energized by closing an adjacent bus tie. It was necessary to conduct these tests with several cables and all available transformers to provide sufficient short-circuit current to clear a network fault.

Immediately following the return to service on an unrestricted basis on March 26, the emergency routing was rapidly converted into a heavy maintenance program. Figure 4 summarizes the progress of service restoration.

Station Pickup Capacity

There are several definite limitations that must be observed in determining the amount of load that can be picked up instantly and yet protect the equipment.

1. The load block that is to be picked up must fall within the overload capacity of the turbine and the steaming capacity of the boilers. The electrical equipment can usually withstand any load the turbine can deliver for a short time. Failure to observe this limitation will result in stalling the system.

2. The load pickup should not be so sudden or be such a large part of the available capacity as to cause priming of boilers with the danger of water carry-over damaging turbine blading.

3. The rate of load pickup on a turbogenerator which has just been rolled and synchronized must be held within the limits set by the manufacturer in order to prevent damage to the blading. This limit is usually about five per cent of the rating per minute. If the shutdown has been of short duration, the turbines which were carrying load preceding the disturbance usually will not have a rate of pickup limitation.

The boiler capacity in general sets the load conditions. Tests on individual boilers show that instantaneous changes in the steaming rate can only be realized when accompanied by a pressure drop using the accumulator effect of the boiler for the sudden increase in output. The curves (figure 5) show the rate at which the steaming rate is increased by an increase of the combustion rate. Powdered-coal boilers respond as shown and can hold the rating after the initial pickup. Stoker boilers are more uncertain in their performance due to the variation in condition of the fuel bed. A stoker boiler with a light fuel bed can produce a high rating for a few minutes but may not be able to hold the output until such time as the fuel bed can be built up for operation at the higher rating. This may require at least one-half hour before the ultimate rating is available.

Repeated tests have indicated that the following pickup ratings can be met in everyday operation. The standby boilers or boilers counted as having reserve capacity should be operated at not less than 15 per cent of their normal rating in order to keep the fuel beds ready for additional load. With this requirement met the boilers are then able rapidly to increase their output to 250 per cent of the initial output, provided the maximum rating of the boilers is not exceeded. The boiler spare capacity is based on this pickup ratio and the same ratio would apply for restoration of system load.

Theoretical studies have been made of boiler performance under these emergency conditions, but these studies, in general, indicate the optimum condition rather than the practical aspect.

One of the definite limitations in the pickup rate is personnel. An emergency load pickup greatly increases the attention required from the boiler operator; for instance, the feed water control is made semiautomatic to reduce the drum level as a preventative of priming, the dampers require resetting, and additional fans may be required. The coal feed is increased, the powdered-fuel boiler burners may require relighting if the auxiliary power supply was lost during the load drop. All these duties must be attended to manually and the rate at which the operating organization can accomplish these moves determines the degree by which the optimum rate of pickup can be reached.

Upon the occurrence of a major shutdown the several power stations immediately take such measures as may be required to hold what load is left or to protect the equipment. In general, the safety of the equipment takes precedence over system service, since once a disturbance has occurred any abnormal risks to equipment may result in further trouble which will require days instead of minutes to remedy. During the emergency the electrical switchboard operator becomes the key man in the stations, contacting the system operator, and advising

the turbine and boiler-room operators of the system conditions and other information as fast as it is available.

The system operator is advised as soon as possible of the general conditions within the plant and furnished an estimate of the pickup capacity and the time required to perform this pickup. During this interval the station conditions will be returned to normal as fast as possible but no attempt will be made to restore service until all the elements contributing to service restoration are under control. Upon the sounding of the emergency alarm, certain picked maintenance men, who have had operating experience report to the turbine room, boiler room, and control room to augment the operating personnel and assist in the extra duties caused by the emergency. In event of loss of communication with the system operator, each plant will attempt to limit the load by opening lines, in order to retain reasonable steam pressures and prevent a general failure of the generating stations.

Experience so far has indicated that conditions on the transmission system and the time interval required by the system operators to co-ordinate the emergency activities retard the rate at which service is restored well within the limits of the power stations.

In order to start up a system which has been shut down, a plan or program must be provided. If, for instance, the flood hazard is great, a flood program is necessary. On the other hand, if shutdown is the result of failure unforeseen, the plan of pickup is determined by the remaining available facilities and the possible setup ensuing at the time. When a failure occurs, the operating personnel goes on its own, the load dispatchers, switchboard operators, and so on down the line must accept and share the responsibility of performing the duties required. Recognition must be made of existing rules governing operation such as overload ratings, equipment protection, and rate of pickup, and all these factors co-ordinated. In conclusion, past experience has proved the need for a pickup program. The major considerations necessary for making two types of plans for start-up are tabulated below and have proved invaluable in the restoration of service.

I. Predetermined Shutdown Caused by Flood

Curtail service in an orderly manner, saving all equipment possible. This expedites the start-up.

Provide system operator with elevations of all equipment in flood area referred to river elevations.

Provide operating departments with detailed instructions giving the required work and material location for protection or salvage at incremental flood stages.

Establish communication facilities. It is necessary to enlarge existing facilities to care for increased traffic. Also emergency radio channels and adequate messenger service are needed. It is essential that boats and automobiles be provided for the messengers.

Provide station service to power stations. Standby interconnections, small oil-engine generator sets for lighting, and small power uses are essential. Steam-driven auxiliaries with stoker boilers are also desirable.

Provide a "priority of service schedule" with the necessary operating instructions to effect immediate restoration of service for public safety or health.

Provide a loading program based on the "priority schedule". This is based on the amount and character of the various service classes. Utilize restriction of service during emergency, either by municipal proclamation or appeal by company executives in order to widen scope of service restoration with limited capacity.

Establish operating personnel routine. It is necessary to provide a training program as part of operating routine to prepare for floods. During the emergency it is necessary to insure adequate food, safe water, and provide shelter and in some cases, clothing for employes. In addition it is essential that an immediate checkup be made of home conditions for those employes retained on duty.

Observe strict limits on total working hours to protect employes from sickness and injury.

II. Shutdown Caused by Failures Not Predetermined

Make a survey of system conditions immediately following a major shutdown of this type. This provides sufficient time to collect thoughts and avoids rash moves which may further damage equipment and thereby complicate service restoration. This further provides sufficient time to determine the status of the power plants and locate the failure.

Provide a plan of restoration. The plan will depend on the facilities available for operation. It is extremely desirable to maintain some firm boiler capacity to initiate the restoration plan. If possible, parallel a part of the generating capacity with available interconnections, and back feed power to the interconnection to establish firm plant capacity. When possible, parallel generating plants through the transmission system to increase the pickup ability. Restrict the rate of service restoration to avoid recurrent curtailment, and if required, segregate the system into load blocks which, when added, will not be in excess of the available turbine or boiler plant capacity. Co-ordinate the rate of service restoration with actual conditions of boilers and other essential power-plant equipment.

Establish a routine for operating personnel. Complete co-ordination is necessary between the load dispatchers and the switchboard operators. Provide plans for augmenting this personnel during emergency, and these plans should be predetermined and included in the operating routing. In conclusion, place complete confidence in the operating personnel to get out of trouble; they are intimately acquainted with their specific phase of operation, and can do the job best.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Restoration of Service From Large Metropolitan System After Complete Shutdown

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Synopsis: This paper sets forth briefly two general procedures that may be followed in starting the system of the Philadelphia Electric Company after a complete shutdown, and also gives some experiences relating to re-establishing service. There is also included an outline of some of the major principles of design followed in the development of the system which are important in minimizing the chance of a complete system shutdown and in facilitating restoration of service in the event of a complete outage.

IT is believed that the problem of expeditiously restoring service from a system in the event it is completely interrupted may be divided essentially into two parts. The first has to do with operating routines which require that the operating men are thoroughly conversant with the many things that they are required to do at such times so that upon instructions from the system operator various activities in connection with restoring service will be carried out with little or no confusion. Needless to say, the process of restoring service is much easier when the layout, both in the stations and in the connections between stations that comprise the backbone of the system is not complicated and has a high degree of uniformity.

The second part of the problem of restoring service has to do with the maximum size of the block of load that must be picked up at one time, which if very large may cause trouble due to automatic opening of circuit breakers or difficulties due to the steaming rate of boiler plants not increasing rapidly enough.

Fortunately, in the case of the Philadelphia Electric Company, there are no single blocks of load large enough to make this a real problem. The largest of the three networks in the central business district of the City of Philadelphia has a peak demand of only about 10,000 kw. The load of the Pennsylvania Railroad Company, while slightly exceeding 100,000 kw, can be split into two parts for the purpose of re-energizing. In this case it is believed that the load will build up to the figure of approximately that before the interruption occurred over a period of several minutes as the trains get under way. The load of the Philadelphia Rapid Transit Company, which is of the order of 100,000 kw, is supplied from a number of different locations and therefore presents no problem in restoring service.

For the reasons outlined in the preceding paragraph, this paper will concern itself mainly with principles of design followed and development of the system in order to facilitate restoration of service, and to the operating procedures followed in order to re-establish service as quickly as possible.

Description of Bulk Power System

The bulk power system of the Philadelphia Electric Company (see figure 1) is that of a divided arrangement of the 66-kv and 220-kv transmission facilities into two backbones of the system; parallelism of the two distinct high-voltage systems being effected on the 13-kv busses through the transformers at the major load centers of the Philadelphia Electric Company and on the 66-kv ring bus of Christiana substation (Wilmington) and the 66-kv busses of Deepwater station. At Conowingo hydro station, the divided arrangement of the 220-kv transmission facilities extends to and includes the 13-kv generator busses.

The major load centers of the Philadelphia Electric Company are the steam generating stations and large high-voltage step-down substations. From these load centers energy is transmitted to distribution substations and to customers having high-voltage service. Customers of this type are also supplied from distribution substations.

The distribution of the generating facilities of the company among the major load centers is such that a satisfactory balance of the generating capacity and area load in each load center is obtained. The comparison of generating facilities and load of each load center is given in table I.

The capacity of the transmission facilities between all load centers, generating, and high-voltage step-down transformer stations, is adequate to make generating capacity of one area available to another for economical system operation or as reserve coverage in providing for the possible loss of generating equipment on any part of the system.

Principles of Design

Some of the general principles of design that are followed are enumerated in the following paragraphs:

1. Generating capacity is provided as close to the load areas as economics and other conditions make practicable, or in other words it is the desire to make each load area as nearly self-sustaining as possible under the circumstances encountered. In the case of generation by hydroelectric plants this is obviously not possible, due to the location of suitable sites being some considerable distance from the load.

2. Simplicity of layout. It has been the practice of this company for a great many years to avoid complication, both in the stations and in connections between stations, in view of the many advantages thus to be obtained.

Table I. Generating Capacities of the Various Load Centers and Approximate Amounts of Load That May Be Supplied Through Each Center

	Generating Capacity (Kw)	Area Load (Kw)
Richmond	255,000	180,000
Delaware	183,000	137,000
Chester	126,000	130,000
Deepwater	58,000	40,000
Schuylkill	179,000	170,000
Paschall		20,000
Conowingo	252,000	3,000
Plymouth Meeting		25,000
Westmoreland*		100,000
Barbadoes Island	45,000	75,000
Total	1,098,000 kw	900,000 kw

* Westmoreland load area included here as in Conowingo load area for the purpose of restoration. Normally it is part of the Richmond-Delaware area.

3. The system is so sectionalized as to minimize the effects of faults. As pointed out, the portion of the system operating at 66 kv is operated to all practical purposes as two separate 66-kv systems, which are interconnected at certain points mentioned earlier in the paper. The operation of the 66-kv system in this manner not only gives lower short-circuit duty on switchgear, etc., but minimizes the disturbance produced under such fault conditions. The sectionalizing of the system is further planned so that failure of any one locality should not reduce the capacity available to carry the load in this particular area below that required for the load involved.

4. Quick clearance of faults. Very much has been done, particularly in recent years, in reducing the length of time required to

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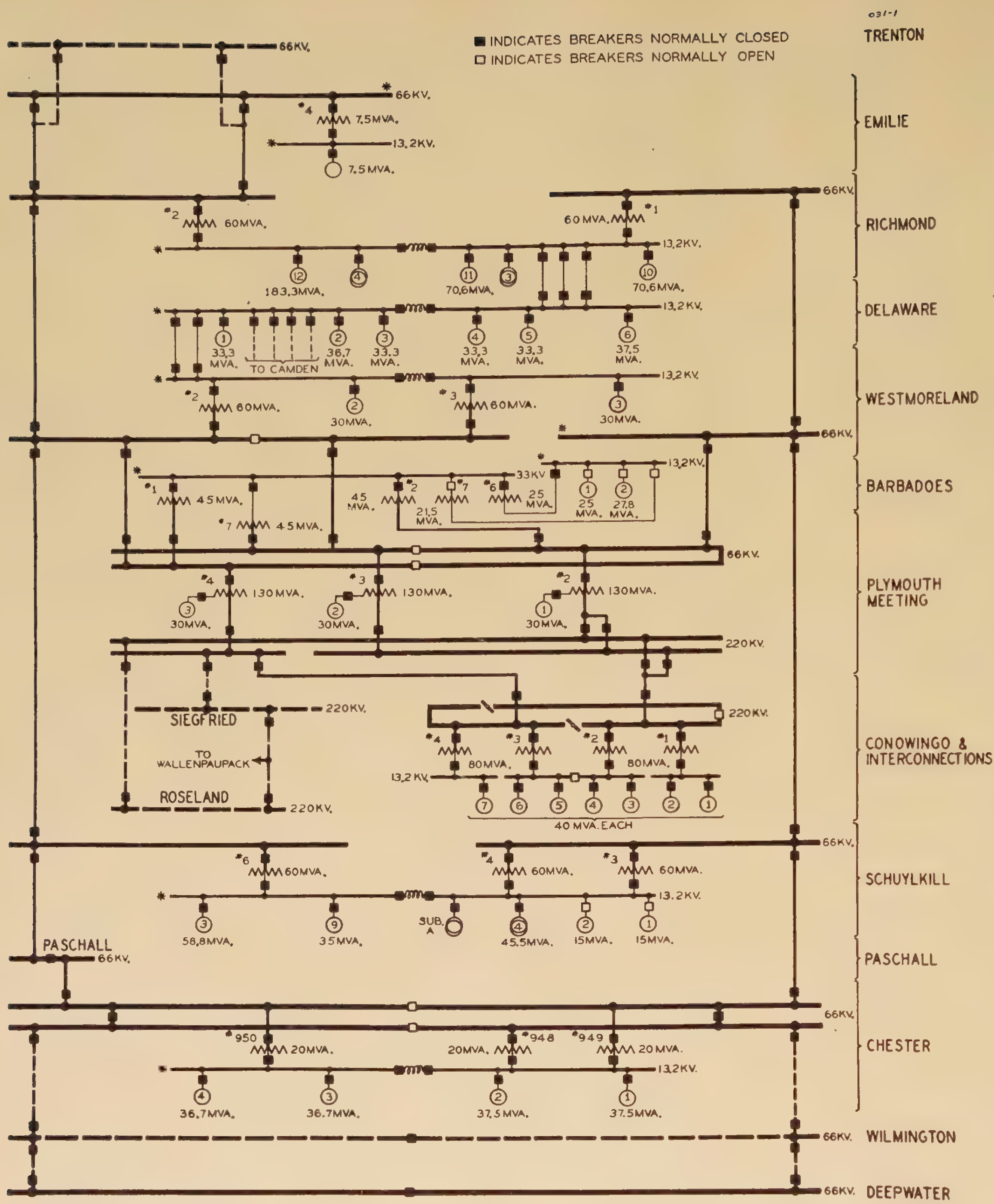


Figure 1. Bulk power system of the Philadelphia Electric Company

In addition to the generating capacities shown in this figure the company has available a capacity of 62,000 kva in the Deepwater plant, which is owned jointly with the Atlantic City Electric Company. At the locations marked with an asterisk busses not normally energized have been omitted for the sake of simplicity. Certain stations of other utilities and the lines connecting with them are shown with broken lines

clear faults on those portions of the system where quick clearing is important. This involves the use of pilot-wire relays on 66-kv cables, differential protection of busses and transformer banks, and for certain applications circuit breakers that will clear a fault within eight cycles (0.13 second).

5. Isolation of equipment. Considerable attention is being given to the arrangement of equipment in switch houses, provision of barriers, etc., to provide a proper degree of isolation in the event of oil fires, explosions, etc. There is now under way complete modernization of the Schuylkill switch house which changes the layout from the present double 13-kv sectionalized bus to a six-section sectionalized ring bus with modern switchgear at the sectionalizing points and at several other important locations. It is believed that a layout of this type should do much to minimize the amount of capacity affected in the event of a fire or explosion. In the case of outdoor substations considerable attention is given to the location and spacing of equipment so that in the event of a failure it will not affect other equipment which is used for reserve purposes.

6. Interconnection. The most important of the interconnections of the system of the Philadelphia Electric Company with other companies is the 220-kv interconnection with the Pennsylvania Power and Light Company and the Public Service Electric and Gas Company of New Jersey. This interconnection not only provides advantages in the way of economy of operation, generator reserve, etc., but is extremely useful in the event of an emergency.

Starting Generating Station From Shutdown State

It has been indicated that each load area of the Philadelphia Electric Company system is adequate unto itself in generating capacity. Thus restoration of the system load should a complete shutdown occur may be a matter of starting each individual station, restoring the area loads and then paralleling the sections of the system to return to normal operation.

The restoration of each generating station is usually dependent on the supply to the auxiliary light and power busses. This supply, in the event of any station

shutdown, may be provided by an electrical feed from an outside source. Failing this, the thermal capacity of the boilers in most of the stations is such that it would be possible to start up the auxiliaries and even a main unit. Thus, steam-driven d-c sets can furnish power for stoker drive and for emergency lighting; a Duplex circulating-pump set can be operated as a generating unit of 200-kw capacity and supply stoker sets, and fans and steam-driven oil pumps can be operated to restore oil-fired boilers. In one station a house turbogenerator is available to carry auxiliary load.

In instances of an individual station shutdown, however, an electrical feed from an outside source would usually be available for supply to the station auxiliary light and power bus and other than the usual starting measures should be unnecessary.

The supply to the electrical auxiliaries of Richmond station is indicated in figure 2. The electric auxiliaries in the other steam stations are supplied from transformer banks stepping down from a 13.2-kv bus and there are no transformers connected to the generator leads and no house turbogenerator.

Restoring the Station Load

When an operating bus has been subjected to an interruption, the bus is cleared; that is, all bus circuit breakers are opened. As the generating sources are restored to the bus, the outgoing lines are gradually restored and at no time will the capacity of these lines exceed that of the restored generating capacity. The operators in distribution and industrial substations restore their load gradually not exceeding the capacity of the lines made available to them.

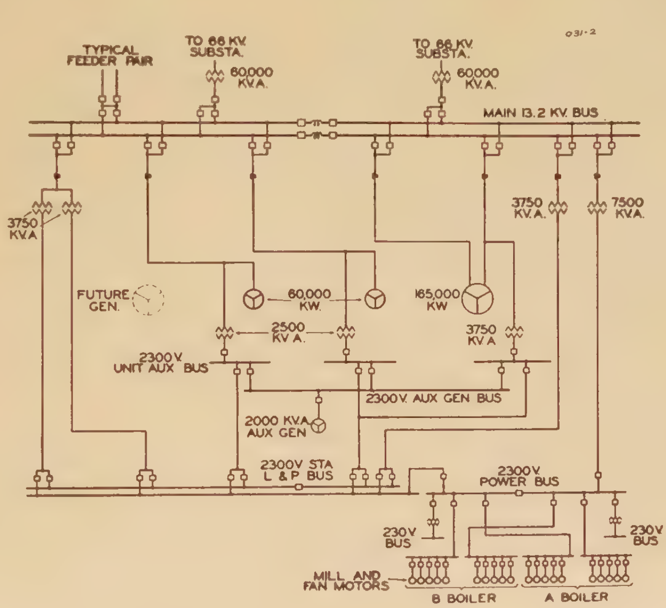
Speed of Load Restoration

The restoration of the load should not proceed too fast for the boiler operators to handle. Delay may arise, however, if the dead busses are not cleared immediately after the interruption, as the simultaneous energizing of a number of large transformers and an appreciable amount of load from one source may cause a severe drop in voltage. This might result in the loss of auxiliaries such as boiler feed pumps and fans. As an instance, at the time of the complete system shutdown of April 4, 1937, the Schuylkill, Chester, and Wilmington areas were simultaneously closed to Deepwater station within a few minutes after the initial outage. The load of these areas just previous to the outage was approximately 90,000 kw. During the interruption, Deepwater station continued to supply the load of the Atlantic City Company and of the Du Pont Manufacturing Company, the combined load being approximately 40,000 kw. When the transformer equipment and considerable of the load of the three areas were simultaneously restored on Deepwater station, the voltage surge caused the loss of a boiler feed pump and the drop in steam pressure delayed the restoration.

In the initial step of restoration, the load of Deepwater station increased from 40,000 kw to 100,000 kw, Deepwater thus picking up all but 30,000 kw of the normal load of the three areas. The steam pressure at Deepwater station fell to 930 pounds, and 19 minutes elapsed before normal pressure, 1,300 pounds, was restored. The load of the three areas required 20 minutes to return to normal.

Figure 2. Auxiliary power layout for Richmond station

This station is the only one on the system of the Philadelphia Electric Company that has a steam-driven house generator



If the bus of each load area had been cleared, the restoration could have proceeded in successive steps rapidly effected as pilot lights indicated the lines had been re-energized.

Operating Procedures

Either of two methods may be followed in starting up the system after a complete shutdown and the choice of method may depend on the normal system load at the time of outage and the generating capacities that had been in operation just previous to the disturbance.

If, for instance, the shutdown occurs in the early morning hours, when Richmond, Schuylkill, and Deepwater stations had been operating at minimum loading, and Conowingo hydro station had been delivering maximum output, the procedure would be as follows, all stations having cleared their dead busses when the outage occurred.

1. Conowingo hydro station; bring all hydro units to synchronous speed.

1*a*. Deepwater station will energize lines to Christiana substation.

1*b*. Christiana substation will energize lines to Chester station and restore its 11-kv load.

1*c*. Chester station will energize its 66-kv busses and 13-kv bus from the Christiana substation 66-kv lines and restore its load.

2. If pilots are not received on 220-kv lines at Conowingo one minute after outage, all units will be closed to bus and both 220-kv lines to Plymouth Meeting substation will be energized.

3. Plymouth Meeting substation will restore the 66-kv lines to Westmoreland substation and Barbadoes Island station, and restore 33-kv lines.

4. Plymouth Meeting substation will parallel with the 220-kv interconnection.

5. Westmoreland substation will energize 66-kv lines to Richmond and Schuylkill stations.

6. Westmoreland substation will restore its 13-kv lines including the Delaware station tie lines.

7. Richmond station will restore its 66-kv and 13-kv lines including the Delaware station tie lines.

7*a*. Delaware station will restore its load on the first group of tie lines to receive a pilot, and then parallel the second group of tie lines.

8. Schuylkill station will energize the 66-kv lines to Chester station and its 13-kv lines.

9. Chester station will restore the system to parallel operation by synchronizing the Schuylkill station and Christiana substation 66-kv lines.

10. Other generating capacities that had been in operation may then be restored.

If the shutdown occurs during a heavy load period the restoration may be effected by each generating station restoring the load of its own area. When this is done, the sections of the system will be paralleled to establish normal operation. In such outages, there is one important rule; namely:

"Clear the dead bus."

As has been mentioned, this means that all circuit breakers of the dead bus must be opened. In restoring the lines and apparatus, this practice will avoid a repetition of the fault without being aware of its location and will prevent a voltage disturbance and the confusion that may arise if too much load is re-energized when the first unit is closed to the bus. The control of the return of the load also may be more satisfactorily maintained in this manner.

Initiative of Station Personnel

The restoration of generating capacity within the station to full speed and voltage is a function of the operating personnel of that station. The availability of an outside supply for the starting of the station auxiliary equipment, however, is a function of the load dispatcher, as is the direction of the energizing of the bus and the restoration of outgoing lines.

Co-operation between the boiler room, turbine room, and switchboard operators of necessity and through the realization by each group of their respective functions is of automatic response. The personnel of the boiler room knows that the station output must be restored to what it was before the disturbance and they also know what their part in the program must be. The personnel of the turbine room are also familiar with their responsibilities and this is also true of the switchboard operators, for the operations all of these men must perform in an emergency are similar to their everyday functions.

It is in the location, inspection, and isolation of faulted equipment that a high degree of initiative is very essential. The confusion that usually attends this type of station failure is usually the cause of undue delay in restoring the station to operation. The electrical supervision must first of all observe the essential safety regulations and see that none of the equipment in the area being inspected is energized until all men have left the scene. His inspection is primarily to determine what equipment may be re-energized and what switching must be done to isolate the faulted equipment. The performance of this function as expeditiously as possible will mean usually that the restoration of the station will be effected without any unnecessary delay.

Other Effects of Shutdown

On the system of the Philadelphia Electric Company the procedure in starting up after a complete shutdown does not require any changes in relay settings or alterations of any nature in the protective scheme.

Regarding the possibility of interference with telephone and signal systems, this is present for the duration of the fault and, in some of the past occurrences, has resulted in trouble on the circuits of a railroad company but has had no apparent effect on the leased telephone communication circuits used by the company.

Conclusion

The possibility of a complete shutdown of the system of the Philadelphia Electric Company is extremely remote, particularly as a result of changes effected in operation and design during the last two years.

The starting up after a complete shutdown, if it should occur, may be effected by starting each individual station separately as the generating capacities and the load of each major distributing center approaches a balance.

The restoration of all but the 25-cycle railroad load should usually be effected within five minutes, and the entire system within ten minutes, provided the functioning of the operating personnel is satisfactory.

So far as can be foreseen at the present time, it is expected that the design of system extensions will follow the same general principles now in use, except that sectionalized ring busses will likely be used more generally in the future instead of double busses.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

The Design and Operation of a Metropolitan Electrical System From the Viewpoint of Possible Major Shutdowns

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Synopsis: The bulk power system of The Detroit Edison Company is designed and operated in five power-plant load areas. These load areas are "loose linked" to prevent uncontrollable trouble in any one of them causing a total shutdown.

The internal design of the load areas is arranged to permit of ready sectionalizing in event of serious area shutdowns, thereby permitting the load to be picked up in small pieces. Such sectionalizing is practicable because the distribution lines are largely radial, that is, are not connected together beyond the substation.

A limited amount of experience data are given on the behavior of generators under instantaneously applied loads.

The rationale of emergency operating is developed and the special instructions outlined.

DESPITE the efforts of central-station operators and designers to the contrary, there occasionally occurs a complete shutdown of an entire major electrical system or a large section of one. Unless, in the design and the operation of the system, proper account has been taken of such a contingency, it may prove very difficult to again "start up" the system and unnecessarily long service outage may result.

Accordingly, it was felt that a symposium covering the design and operating practice of several large systems with respect to "starting up" would prove helpful to those facing such a problem. It is as a part of such a symposium that this paper is presented.

In any particular situation the difficulty of starting from complete shutdown, turns in the last analysis on the degree to which the load itself may be divided into discrete pieces, small enough to be picked up by the available generating capacity.

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General

On a system where the load consists largely of primary or secondary networks it is desirable, in the interest of economy, to make the individual blocks of load or "pools" as large as can, with certainty, be picked up by the generating capacity available and by the number of feeders which the operators can simultaneously close onto the busses. In the design of such a system it is necessary to have a fairly accurate idea of the performance of generators under suddenly applied loads or overloads, and also how the load may be expected to vary with reduced voltage and perhaps reduced frequency. While some testing and a great deal of calculating have been done, the most reliable knowledge must of necessity come from the actual experiences of systems under emergency conditions and one of the principal purposes of this symposium is to bring forth reliable experience data of that kind.

On the other hand, in a system employing radial distribution lines beyond the substation, that is, lines which are not connected together, the load is already divided into relatively small pieces which can, if necessary, be picked up one at a time in detail.

Accordingly, the approach to the "start up" problem is determined by the character of the load area served and becomes a question of designing to meet the particular situation.

With the exception of a square mile or so, the territory of The Detroit Edison Company lends itself to the use of radial overhead distribution lines. Very few of the radial circuits have loads in excess of 1,500 kilowatts. Thus, there is no problem in picking up the individual circuits. In fact, in most cases, there is little difficulty in picking up whole distribution substations. Accordingly, this paper will be largely confined to the design of the metropolitan system to restrict shutdowns to limited areas and to the emergency operation of such a system.

The Bulk-Power System

Fundamental Design

To guard against the possibility of total shutdowns, the design of the bulk power system of The Detroit Edison Company is based on two principles.

The first principle is that the system shall be divided into several load areas (at present five) so interconnected that, should an uncontrollable fault persist in any load area, this area with its prime power source will disconnect itself from the system, thereby permitting the remainder of the system to go on its way. Also, each load area must, within reasonable limits, be self-sustaining since it may have to start up by itself and perhaps run that way for a time. This principle has been dubbed "loose linking."

The second principle is almost corollary to the first and is, that with any load area disconnected the remainder of the system shall be self-sustaining, that is, shall be able to carry its load at normal frequency and voltage.

Figure 1 is a diagram of the bulk power system of The Detroit Edison Company. You will note that there are five power-plant load areas held together at what are termed "interlinking points." Each "interlinking point" is indicated by a small rectangle with a diagonal line drawn through it. The solid black rectangles represent the ones in use at the time and the open rectangles the alternates.

While the design principles outlined above appear simple, there are several implications which in practice call for care in design as well as in operation. The first implication is that, since an uncontrollable fault is one which is not cleared by the normal protective equipment, the operation of the system sectionalizing circuit breakers at "interlinking points" must be delayed until the internal protective gear has had opportunity to clear the fault if it can do so, that is, until the fault has really become uncontrollable. (Needless to say, several successive steps of protective gear must have simultaneously failed before a fault becomes uncontrollable.) This necessary time delay at the interlinking points may amount to several seconds which might be troublesome to the other load areas from the point of view of stability of generators. Therefore, it is necessary to have sufficient impedance in the interlinking ties so that, under the worst fault conditions, the voltage in neighboring

areas will not fall low enough to cause generator instability in those areas. Based on calculations and such experience as we have had to date, the amount of the line impedance necessary to control short-circuit duty appears to be enough to accomplish this. So far, there has occurred one case of bus trouble which operated the interlinking points of its load area. No generator stability troubles occurred either in the faulted load area or any of its neighbors.

Another implication of these design principles is that the load included in any load area must be adjustable to the amount of generating capacity available to the load area. Not only must these conditions be met at peak load, but the system must sometimes be altered to meet the various generating requirement up with high-economy generating equipment. You will note from the position of the interlinking points in use, the black squares labeled A, that the load area is now widely extended. During the rebuilding period at Conners Creek, it was at one time contracted to the condition shown by the interlinking points labeled B.

An interesting variant of this principle exists at the Trenton Channel plant. There the plant operates in two parts, each of which serves a separate load area. It was relatively easy to make several of the generators "double throw," so to speak, and thus make them available to either load area. Thereby, we can, within limits, adjust the generating capacity to the area load, and we therefore do not need so great a proportion of trans-

Load Area Internal Design

Figure 2 shows the internal arrangement of a typical city power-plant load area, that is, where 24-kv underground transmission is used.

By a series of heavy dotted lines there is shown the physical segregation of the equipment and lines into zones extending from the generating station to the customer. Within these zones the radial distribution lines may be picked up one at a time if necessary to aid in restoring service.

Beginning with the generating plant, you will note that the generators and the tie cables to the adjacent plant areas are held together by a star-connected synchronizing bus and its reactors S. The synchronizing bus and reactors are care-

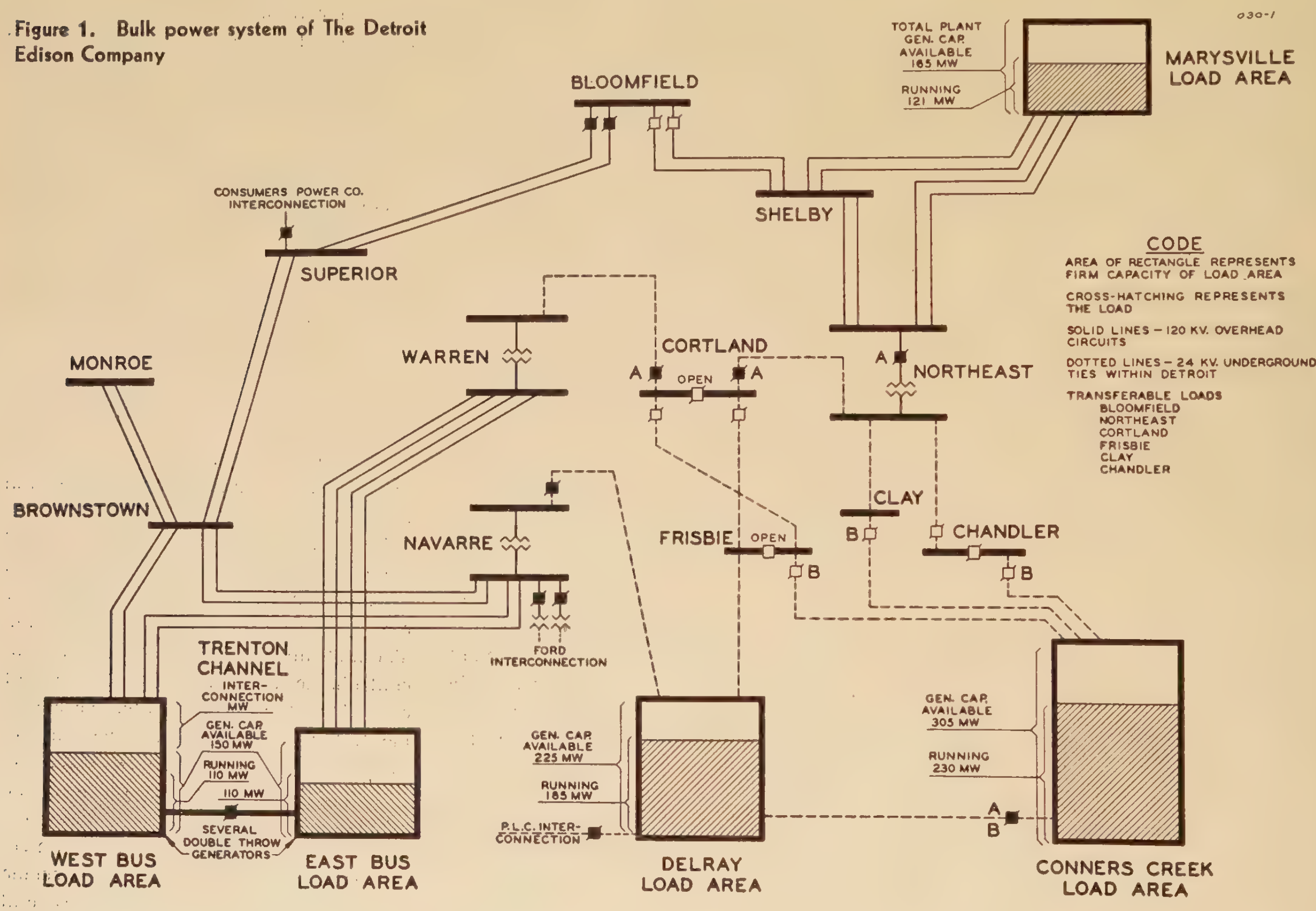

Figure 1. Bulk power system of The Detroit Edison Company

throughout the day. This may be particularly true during light load periods when the more economical plants are favored as to loading.

Further reference to figure 1 shows the bulk power system as it has been worked out to meet these conditions.

As an illustration of how load areas are adjusted, refer to the Conners Creek load area. At present, that plant is well built ferable load to maintain the load areas on a self-sustaining basis.

Summarizing briefly, while we contemplate the complete shutdown of only one power-plant load area at a time, nevertheless each of the areas could be started simultaneously from standstill if necessary. Accordingly the problem of starting up becomes, for this system, one of the internal design of the load area.

fully segregated from all other bus and switch rooms for the purpose of protecting them from the troubles arising elsewhere in the switch house. Next you will note that each set of generator switches and its "feeder gangs," as well as each set of tie line breakers G, is separated from the others by careful sectionalizing of the switch house. Also, the busses and all connections are completely

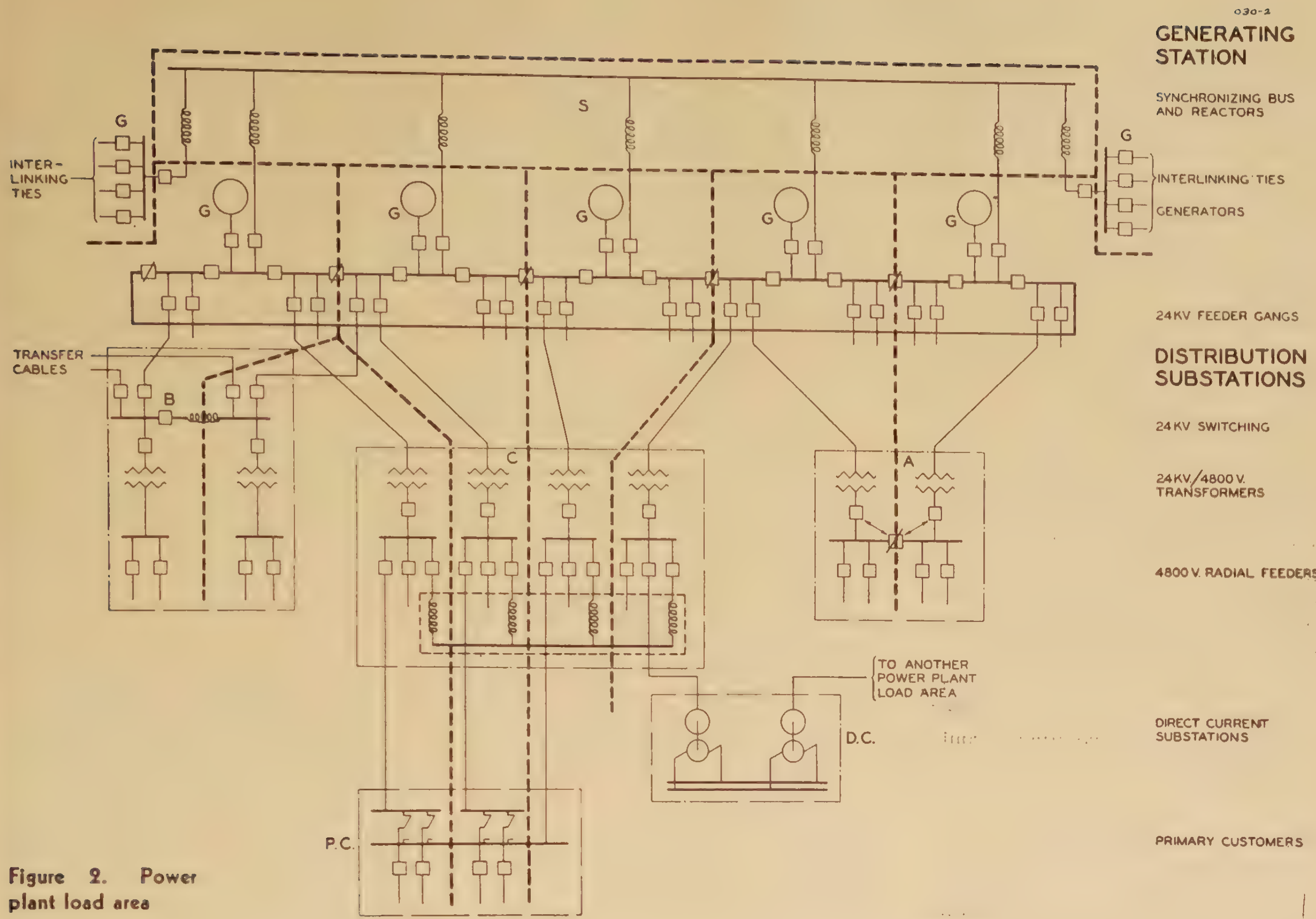

Figure 2. Power plant load area

metal clad and each phase segregated in its own metal enclosure.

In the load area are three kinds of substations. One kind (*B*) has 24-kv switching and usually serves not only as a "satellite center" for the collecting of large industrial and small substation loads, but also as a transferable load to aid in adjusting the size of the load area. Each of its bus sections is separated in a manner similar to the generating-station switch house. Substations of this kind are costly to build and to man but fortunately not many of them are required.

A second kind (*C*) is that commonly used to supply heavy industrial and commercial areas. Such a substation has no 24-kv switching. Its transformers are connected together on their 4.8-kv side by a star-connected synchronizing bus with its reactors which is carefully segregated from the other busses and equipment. The switchgear for each transformer and its "feeder gangs" is also segregated from its neighbors.

A third kind (*A*) is that having no 24-kv switching and no 4.8-kv synchronizing bus or reactors. Each transformer serves a "gang" of 4.8-kv feeders and is so arranged that, should a transformer or the 24-kv cable feeding it fail, its "gang" of feeders will be automatically thrown onto the spare transformer capacity with an outage of some two seconds.

A fourth type (D.C.) is the d-c substation, each of which is fed from at least two separate power-plant load areas and often from three, so that the loss of any power-plant load area will not cripple any d-c substation. Should there be a complete shutdown of all the power areas feeding the d-c system, the d-c load will be picked up by motor generator sets which are equipped with load-limiting apparatus for that purpose.

A fifth type is the a-c network in the downtown area. These are not shown on figure 2. We do not contemplate that any of these networks as laid out is likely to exceed 10,000-kw load. Each is normally fed at 4.8 kv from a substation in one power-plant load area and arranged to be transferred to a substation fed from another power-plant area should the first one fail. The quantities of load involved are not sufficient to present any problem in picking them up.

A sixth type is the primary customer installation (P.C.). Care is taken to see that each feed to such a customer is served from a separate section of supply substation or from separate substations.

In figure 3 there is shown the methods of serving a load area by overhead 120-kv transmission lines. Here the segregation of trouble is not quite so complete but each 120-kv bus section is separately relayed to localize trouble. Also, each 24-kv bus section is carefully segregated by steel barrier walls and double section switches and the 24-kv lines to distribution substations are spread over the bus sections in the same manner as described for the typical power-plant load area. While we have not shown them, the distribution substations are of the same type as shown in figure 2. Again, the dotted lines show the zones of segregation.

From the above description, it is evident that there is no fundamental obstacle to the starting of such a system from a complete shutdown because the load can be picked up in small enough pieces to be well within safe limits for generators and boiler plant.

Auxiliary Supply

Generating Plants

It is the practice of the company in each of its generating plants to provide completely independent steam-turbine-driven d-c generators to supply most of

those essential auxiliaries which are electrically driven. The principal exceptions are some of the larger boiler feed pumps where system-fed a-c motor drives are used. In these cases, steam-turbine-driven pumps are also provided.

The reasons for so doing are two. One is to shield essential auxiliaries from disturbances arising on the electrical system, and the other to gain the desirable speed regulating characteristics of d-c motors. With such an arrangement, service to power-plant auxiliaries will not be affected by system shutdowns.

Main Switching Stations

While no particular provision has been made for the simultaneous closing of a large number of the 24-kv feeder breakers, it is believed that three could be closed at once. However, there is little need for the simultaneous closing of even that many since the size of the pieces of load can readily be kept down to what a single outgoing feeder can safely carry for a half hour or so. The circuit breakers are all d-c operated from a control storage battery.

Emergency Loading Experience

While we have had some experience in the matter of suddenly applied overload on generators, most of that experience occurred some years ago before particular interest in that aspect of the problem had been aroused and the records and our memories are not too specific. However, there is a partial record of one case in which a group of generators were suddenly loaded from 80 per cent to about 125 per cent of rating without change of field excitation. The voltage dropped to about 80 per cent of normal and the frequency to 58 cycles, but no generator dropped its load. The short-circuit ratio of these generators probably varied from 0.9 to 1.6, the latter being for the older vertical Curtis turbine then in use. The record contains no statement as to the change in character of the load with that change of voltage and frequency. This case is cited for what it may be worth, recognizing its limitations.

No field tests have been made to determine the change in system load with variation of the voltage or frequency.

The proportion of the load of an area which will immediately be picked up on restoration of service will, of course, vary with the character of the area load. For The Detroit Edison Company system, which is heavily industrial, experience has shown that 40 to 60 per cent of the

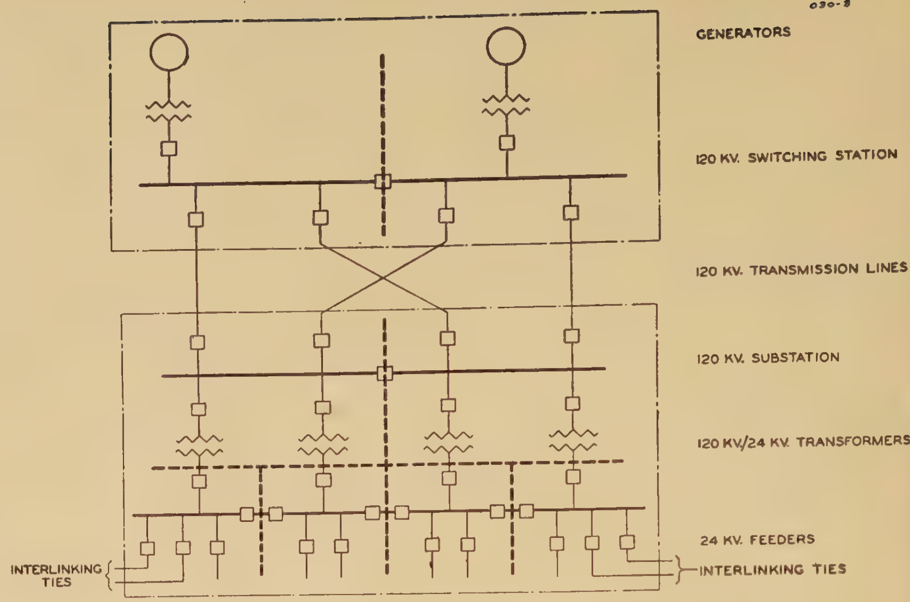

Figure 3. 120-kv load-area supply

original load will be immediately picked up and that the remainder will come back in five minutes or so.

Emergency Operating Procedure

In general, the approach to this question is as follows:

1. Through equipment segregation and by relay and switchgear equipment, means are provided to disconnect automatically and confine most any form of trouble we can foresee.

2. If, for any reason, the several lines of defense provided by the above shall have successively failed and the fault becomes uncontrollable, it is desirable that the operators *immediately* supplement the protective equipment by whatever action is necessary to localize and clear the fault, bearing in mind that the first concern is for the safety of the system as a whole and thereafter for the particular load area or substation, as the case may be. To guide them in so doing, standard emergency switching instructions have been developed. These instructions are designed to be carried out on the initiative of the power plant and substation operators without recourse to the system supervisors wherever that is practicable—and it usually is.

3. If, despite, the automatic protective gear and the action of operators, the system or any of its load areas goes completely dead, the central system supervisors will take control, since the moves necessary to restore service will probably extend outside the ken of any one group of operators.

Because the action necessary to restore service may vary so widely and because of the broad experience and good judgment of the central system supervisors, we have not so far attempted any specific emergency instructions for their guidance.

Perhaps the best way to illustrate the effect of this approach is to outline the procedure followed in emergencies.

When the equivalent of lamp voltage falls to 80 volts at a power plant or 70 volts at a transmission step-down station and remains so for one minute or more, the operator, without instruction from the system supervisor, takes steps to sectionalize the system by opening the particular interlinking points in use at the moment. If, thereafter, the voltage still remains low, he will sectionalize his busses along the lines indicated by the dotted lines in figures 2 or 3, as the case may be, beginning with whichever section he thinks most likely to be in trouble. As soon as the faulted section is cleared, the operator calls the system supervisor and reports the situation.

It is interesting to note that the index upon which the necessity for emergency switching turns is the voltmeter reading. It has been found from experience that, under fault conditions, the behavior of current-indicating devices is often so erratic as to make them undependable and that persisting low voltage is about the only reliable criterion.

Suppose, now, that the trouble has been so serious that an entire plant and its load area is down and that the situation has been referred to the central system supervisors. The first step would probably be to survey the switchgear and busses to determine what bus sections were in condition to go back into service. Following this, all outgoing lines would probably be opened. Thereafter, the running generators would be brought up to speed, one at a time, connected to a considerable section of bus, and loaded by closing the outgoing feeders one at a time. The generators would be synchronized with the synchronizing bus if it were in commission. If not, they would

be synchronized to their neighboring generators. When everything was again running, if the synchronizing bus were out of commission, the generator busses might be sectionalized into two parts, if need be, to minimize short-circuit duty.

There is only one precaution to be observed in closing the outgoing feeders and that applies to the feeders running to the industrial substations (*C* in figure 2). These feeders, being tied together through a 4.8-kv synchronizing bus, the system supervisor might find it necessary to open these synchronizing bus ties to prevent overloading of the first feeders to be closed in. This can readily be done.

With respect to the boiler plant, there should be little difficulty because the load will not be picked up in large pieces. An ample supply of make-up water is held in reserve to replace any loss due to the blowing of safety valves.

It is not necessary to alter any relay settings, either at the power plants or at the substations.

To guard against a failure of communication facilities, the company has built up a private telephone system connecting the system supervisors with each generating plant and each principal substation. This is supplemented by Bell System phones. In the case of the Trenton Channel and Marysville power plants, which are more remote from the system supervisors, there is also provided carrier-current communication. There is, in addition, radio telegraph to the Marysville plant. Very rarely have we had to use either the carrier-current or the radiotelegraphic communication. The chance of a simultaneous failure of these communication facilities is very small but, if that contingency did arise and the operators could not communicate with the central system supervisors, they are instructed to proceed to restore service within their own area or substation on their own initiative.

While the power plant and substation operators are required to become very familiar with operating instructions affecting restoration of service, no specific rehearsals have been conducted. It is felt that any of the instructions are so much in line with the steps which would normally be taken by an experienced operator as to preclude the necessity of staged rehearsals.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Provisions for Re-energizing the Electric System of the Consolidated Edison Company of New York, Inc.

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IN the course of the last three or four years there have been a few instances in which generating stations supplying electric service in large metropolitan systems have shut down temporarily because of storms and floods of unusual severity or because of accidents resulting in fires which could not be quickly brought under control. These occurrences, while fortunately very infrequent, have focussed attention upon the problem of starting up a large system in the event of a complete shutdown of one or more generating stations supplying it. It is therefore the purpose of this paper to present:

1. Some of the more important considerations affecting the design of the distribution system and the generating stations in the Consolidated Edison system with respect to the ability to restore service after a complete shutdown.

2. The principal features of the operations involved in re-energizing the electric system, in accordance with a predetermined plan.

3. A review of some operating experiences related to the problem of re-energizing the system.

Description of the System

The Consolidated Edison system furnishes electric service to all of Greater New York City, with the exception of the borough of Richmond and a small portion of the borough of Queens. It also supplies nearly all of Westchester County.

Approximately 2,400,000 consumers are served in an area of about 700 square miles having a total population of nearly 8,000,000.

The electrical supply is derived principally from 11 steam generating stations located within the territory served and having a total installed capacity of 2,556,000 kilowatts. About 70 per cent of the generating capacity operates at 60 cycles and the remainder at 25 cycles.

All of the generating stations are interconnected by direct tie feeders for each of the two frequencies and by five frequency changers having a combined capacity of 190,000 kilowatts. This system normally operates in parallel with the system of the Niagara-Hudson Corporation through a 60-cycle connection of 200,000-kva capacity and with the system of the Brooklyn-Manhattan Transit Corporation through a 25-cycle connection of 40,000-kva capacity.

Figure 1 is an outline map of the territory served showing the location of each generating station.

Figure 2 is a single-line diagram showing the connections between generating stations, their net generating capacity, and the estimated district loads at the time of the peak in 1939.

The 60-cycle system supplies, in all parts of the territory served, residential, general commercial, and industrial loads as well as the entire load of the municipal rapid-transit system. The 60-cycle load at the time of the system peak represents about 70 per cent of the total load.

The 25-cycle system supplies a large d-c traction load which includes the terminal divisions of all of the trunk-line railroads entering New York City; a large d-c load for residential and commercial use, mostly in the borough of Manhattan; a small amount of a-c commercial load, and some single-phase a-c traction load.

The total system load at the time of the peak in 1939 was 1,704,000 kilowatts. The energy distributed during that year was slightly over $7^1/_4$ billion kilowatt-hours.

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The authors wish to express their appreciation of the advice and assistance rendered by W. E. Caldwell, mechanical plant engineer of the Consolidated Edison Company, in the preparation of this paper.

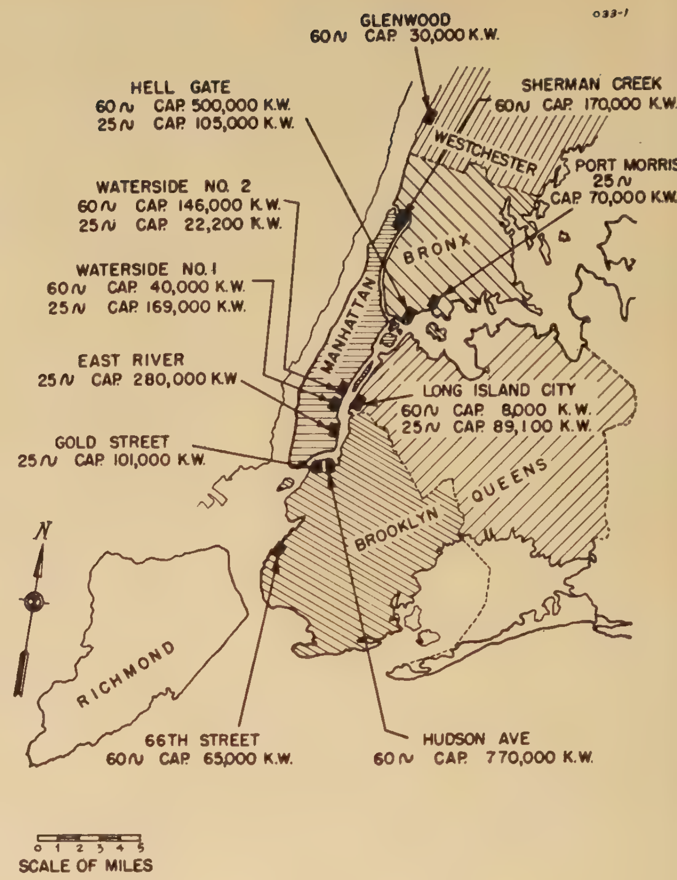


Figure 1. Territory supplied by the Consolidated Edison system and the locations of the generating stations

Fundamental Considerations Affecting the Design of the Distribution System and the Generating Stations

Electric distribution systems and their sources of supply are designed so as to provide electric service of the highest quality that the density and character of the load will justify. Probably the most important measure of this quality is that the service shall be substantially free from interruption. However, equally important from a system standpoint, is the ability to restore service quickly after an interruption may occur and with little or no damage to equipment during the shutting down or re-energizing periods. In suburban and rural areas the radial type of electric distribution provides service which is rarely interrupted and at a cost sufficiently low so as to be commercially practical. With such a system the load is divided into units which are small in relation to the capacity of the sources of supply and the switching of these units is directly under the control of the local operating personnel. The procedure to be followed in restoring service to a radial system consists of reconnecting to the substations and generating source only such load as those stations and the associated feeders can safely carry. Furthermore, the radial distribution feeders are practically self-protecting in that the feeders and associated load are simultaneously interrupted and therefore do not suffer damage during system shutdown.

To provide the high degree of service continuity required in metropolitan areas, the multiple-feed low-voltage network was developed. This form of distribution has been used continuously since the establishment of d-c service from the Edison system in New York in 1882. The development of the a-c network protector led to the application of the same principle to a-c distribution in Manhattan in 1922. Operating experience including the operating record of cable limiters has demonstrated the high degree of reliability of the low-voltage network and that the over-all service reliability is dependent almost entirely on the reliability of the sources which supply the network. It is not economical or reasonable to provide for the maintenance of continuous service throughout every conceivable contingency condition nor for contingencies having a frequency probability so low that they can be disregarded. Furthermore, not every contingency of nature can be foreseen. It is essential therefore that means be provided for re-energizing individual networks or a system comprising a number of networks.

The system plan adopted by the Consolidated Edison Company contemplates that the generating stations will be interconnected normally by a system of direct tie feeders and frequency changers only and that the total distribution load will be segregated into blocks, which, even at peak-load conditions, are small by comparison with the capacity of the interconnected stations. The existing area segregations are shown in figure 3.

While network areas should be small for facility in restarting after shutdown they should not be made too small as the distribution layout thereby becomes relatively expensive. For a system as extensive as that in New York, we believe that each a-c network should be supplied by from 8 to 12 high-voltage feeders. In order to load these feeders, consisting of three-conductor 800,000-circular-mil cable at 13 kv and three-conductor 500,000-circular-mil cable at 27 kv to reasonable values, it follows that networks supplied by feeders at the lower voltage should range in capacity from 50 to 75 megawatts, and from 75 to 150 megawatts if supplied at the higher distribution voltage. Not all of the areas supplied from a given station need be kept to the minimum values as a station should be able to restart progressively larger units as re-energizing proceeds. If some areas are too large they cannot be selected for initial restarting. In the absence of extensive experience in restarting networks, the above values of area load ranging from five to ten per cent of the system peak load are largely based on opinion but are believed to be conservative. Moreover the limitation of an a-c network to a size appropriate for supply derived from 12 feeders makes it necessary to operate simultaneously only a moderate number of circuit breakers at the instant of restarting.

When the load in a segregated a-c network approaches the above values, the network is subdivided and in some instances regrouped to form other segregated networks whose physical boundaries and primary feeder rearrangements have been previously planned and partially installed in advance of the load growth.

Each primary feeder to a segregated a-c network should supply load in only that one area. If this requirement is not observed, it would be impossible to energize one network without energizing equipment in other networks at the same time. This would either mean starting a number of networks simultaneously; damage to equipment in other networks not being energized; or delaying the starting up until the slow process of

blocking open protectors in conflicting areas can be completed. A network to be suitable for independent restarting must be segregated both primary and secondary from other networks.

All of the primary feeders to a given a-c network area should, in our opinion, derive their supply from the electrical galleries of one generating station. During unusual operations such as the restoration of service after shutdown, such an arrangement minimizes the amount of operating co-ordination required and thereby simplifies the operating rules covering the re-energizing procedure. Furthermore, in the event that communication between stations or the direct tie feeders interconnecting them are interrupted such a plan enables a station to operate as an independent unit usually able to supply the load of the area it serves.

Since the 60-cycle load in an entire area is to be supplied from one station under this plan it follows that electrical and mechanical segregation should be provided to such a degree as to protect the continuity of service during reasonable contingencies. Thus the main bus should be divided into a number of major sections, each separated by gas-tight fire walls so that trouble in one section will not physically communicate to another. Electrical ties between major bus sections which are normally alive should connect through the fire walls by indirect paths such as a synchronizing bus and there should be a minimum of two sets of independent switching and protective gear between a section on which a fault is assumed to occur and other sections. One set of protective gear between a common synchronizing bus and each load bus would seem sufficient on the assumption that not more than one set of protective gear will fail to function properly during a given fault.

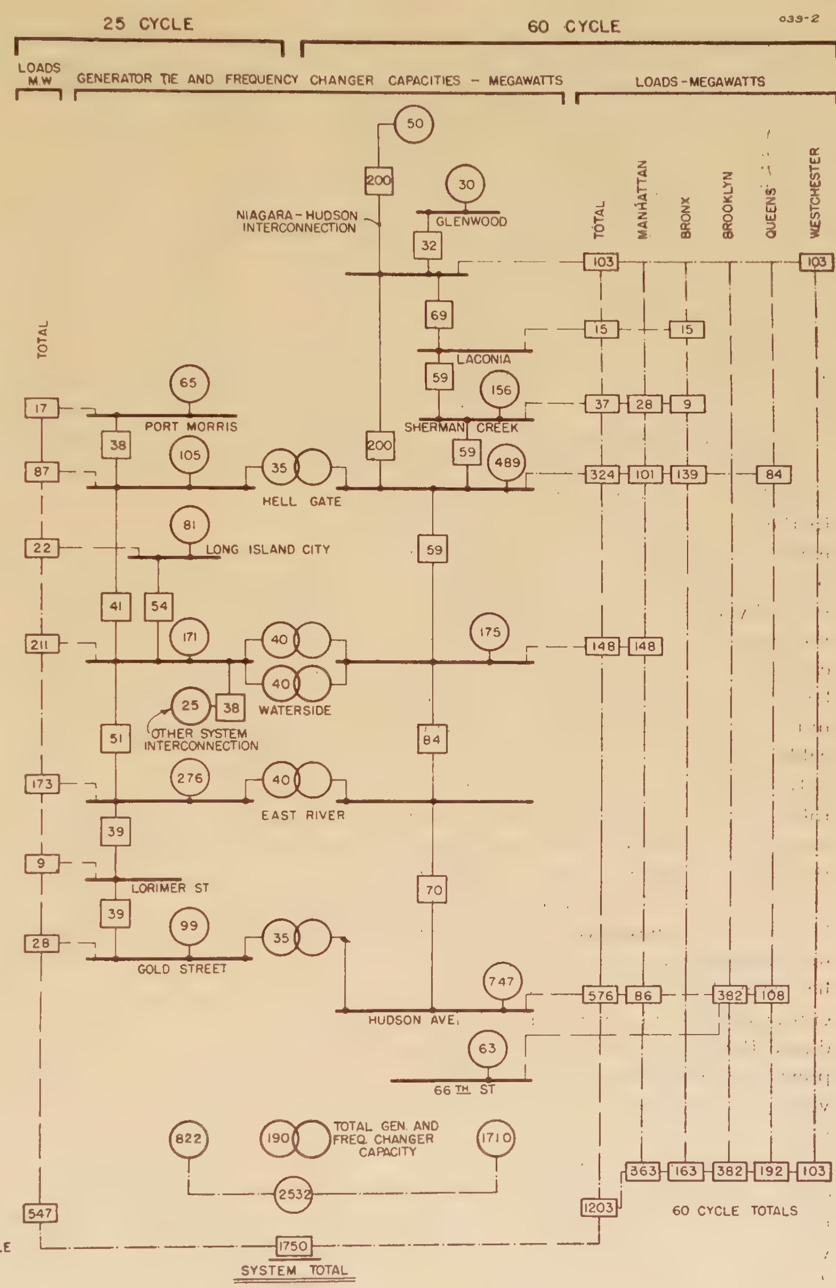
The primary feeders to each a-c network should be divided among the major sections and sufficient network transformer and mains cable capacity should be installed so that in emergency the peak load can be carried or re-energized after shutdown with one major bus section out of service.

The number of major segregations provided at the station should be such that the lowest over-all system costs result. The less the number of major sections provided in the station, the greater is the percentage of reserve equipment capacity on the network system required for operation with one section out. Experience indicates that a station can be economically limited to two major sections only when the a-c networks supplied from it are small and in the early stages of development. With networks of moderate or large size at least three and probably four major sections are economical.

Each major section may be divided

Figure 2. Principal system tie connections and sources of supply for district loads

Generator ratings are net



into two or more subsections further to promote reliability in which case differential protection or its equivalent should be provided on each section.

The d-c control supply and the control wiring in the 60-cycle generating stations must be adequate to permit the simultaneous closing of the requisite number of circuit breakers for restarting a network. The relaying must be such that the feeders will not trip out at the moment of re-energizing due to the current surge.

In the foregoing paragraphs the more significant design features of the a-c network distribution system in New York have been mentioned. While many of these features are considered applicable to d-c network distribution, the development of the much older d-c system progressed along different lines.

D-c network distribution is confined to an area of about 19 square miles in the borough of Manhattan. There is also a very small amount of d-c load in Brooklyn. The Manhattan d-c network is not divided into segregated areas but con-

Table I. Network and Radial Loads in Segregated 60-Cycle Load Areas Shown in Figure 3

All Load Values Are Estimated for the Time of the Peak in 1939

Area Reference Letter	Area Name	Radial Load Excluding Railroads (Megawatts)	Radial Railroad Load (Megawatts)	Network Load (Megawatts)	Total Load (Megawatts)
A	Northeast Bronx	11*	1	3	15
B	Washington Heights	6*	8	23	37
C	Southeast Bronx	5	1	7	13
D	Central Bronx	12*	0	29	41
E	West Bronx	16*	10	59	85
F	Harlem	1*	6	32	39
G	Central Park	5*	7	50	62
J	North Queens	15	8	61	84
H	Times Square	2	12	73	87
K	Madison Square	1	6	54	61
L	Lower Manhattan	2	11	73	86
M	Ridgewood	22*	16	102	140
N	Jamaica	16	2	37	55
P	East Brooklyn	48*	2	66	116
R	West Brooklyn	60*	17	102	179

* Denotes radial load of which a substantial part can be restored independently of the network load.

sists of a continuous grid supplied from 41 d-c substations over approximately 2,400 low-voltage feeders. Cable limiters are installed in all d-c mains at the boundaries of zones supplied by the d-c feeders from adjacent substations.

Each of the d-c feeders is connected to the network mains through an automatic air circuit breaker installed in a junction box. These breakers are closed manually but will trip automatically in the event of a feeder fault when the arc causes the breakdown of insulation on a lightly insulated control wire embedded in the outer layer of strands of the feeder cable.

It is expected that in the event of a total interruption of d-c supply from a given substation the limiters will blow if the current flowing to the affected area over the mains cables reaches sufficiently high values to cause severe cable damage unless interrupted. Sufficient experience has been obtained with cable-limiter operation during faults on mains cable to indicate that the limiters are effective in preventing widespread damage to low-voltage mains cable during fault conditions.

Re-energizing the d-c network in the event of a complete shutdown requires that a selected group of about six low-voltage feeders from each of more than 25 substations be re-energized simultaneously and that the remaining d-c feeders from all 41 substations be cut in as rapidly thereafter as practicable. The operations required for starting the large number of converters upon restoration of 25-cycle supply; connection of these converters to an isolated d-c bus in each substation; connection of the dead feeders selected for initial re-energizing to another isolated bus and particularly the operation of tying these two isolated busses together in the selected substations at the same instant require very close co-ordination for which a special emergency telegraph signaling system has been provided.

Responsibility for Co-ordination and Execution of Operations in Re-energizing the System

Responsibility for co-ordinating operations in the electric system of the company is assigned to the system and district operators.

It is the system operator's responsibility to direct the operation of production facilities so as to maintain sufficient generator, tie feeder, and frequency-changer capacity in service to meet the requirements of the load connected to each generating-station bus. In the event that one or more generating stations are shut down and are ready to resume operation, the system operator is responsible for determining the order in which these stations or reserve stations are to be started up. He will order the re-energizing of busses, reconnection of tie feeders and frequency changers, and will determine in conjunction with the district operators the order in which the segregated loads are to be re-energized to utilize capacity to the best advantage as it is made available.

The district operators in each of the three districts established for convenience in administration are responsible for the direction of distribution operations in their respective districts. It is their responsibility to direct the switching operations in the field and in the stations which are required to re-energize each load area as capacity is made available after shutdown.

The generating station operators and substation operators are responsible for disconnecting all feeders, generators, and frequency changers in the event of the complete shutdown of a given station. They also are required to perform, on their own initiative, specified preliminary operations to prepare for re-energizing the system.

While it is expected that in any emergency involving the shutdown of one or more generating stations, the operations performed in restoring service would be co-ordinated by the system operator and district operators in the manner previously described, it is recognized that a concurrent failure of communication facilities might make it imperative for the switchboard operator at the generating station to assume the initiative in restoring part or all of the load as soon as the station is prepared to do so. The distribution system is designed to facilitate re-energizing in this manner. Several proposals are being investigated in an effort to develop a standard procedure which the individual generating station operators could follow in the event that communication is interrupted and it is necessary to restore the direct tie feeders in order to obtain assistance from an adjacent station when re-energizing blocks of network load.

Written instructions covering the procedure to be followed by the generating station and substation operating personnel in the event of a complete shutdown of any station are revised and reissued as often as required by changes in system facilities.

In determining the form and contents of the instructions simplicity and conciseness were emphasized so that they can be used for quick reference when necessary, and to encourage frequent review by the individuals concerned and thereby to promote their familiarity with prescribed procedure. It is recognized that it is impractical to prepare, in advance, complete and specific instructions to apply to a very large number of assumed emergency conditions. The instructions for re-energizing the system are therefore written to cover selected cases including:

1. The shutdown of each 60-cycle generating station separately.
2. The shutdown of all 60-cycle generating stations.
3. The shutdown of the entire d-c network in Manhattan and the associated 25-cycle system.

Procedure for Re-energizing the System

It is assumed, for the purpose of this discussion, that the entire electrical system of the Consolidated Edison Company has been shut down, that the generating stations are in a cold condition, that the electrical ties with other utility systems such as the Niagara Hudson Corporation and the Brooklyn-Manhattan Transit Corporation are open, that all distribution feeder load has been disconnected and that all generators, frequency changers, and tie feeders have been disconnected. This represents the most difficult condition to be met from the standpoint of complexity of the operations required to start up the system.

In the extreme condition where no power is assumed to be available from other utility systems it would be necessary to establish a supply of electrical energy sufficient to meet the initial requirements of electrically driven auxiliaries. If the tie feeders between generating stations are available auxiliary power can be made available to all stations by starting one main 60-cycle or 25-cycle unit in any one of several stations. The Hell Gate and Hudson Avenue stations have house turbine-generator sets which can be started on steam generated by natural draft in the stoker-fired boilers. These generators can provide sufficient auxiliary power for operation of at least two of the main turbogenerators ranging in size from 35,000 kw to 50,000 kw in either station. If a 25-cycle turbogenerator in a station having steam-driven auxiliaries is selected for initial starting, it can be used to energize the 25-cycle busses in all stations and the 35,000-kw frequency changer at Hell Gate station may be started and used to energize the 60-cycle busses in all stations.

With the main 60-cycle busses and 25-cycle busses energized and a supply of auxiliary power available in all stations the next step would be to start and synchronize the remaining frequency changers so as to complete the restoration of all interconnections among the generating stations in the Consolidated Edison system.

In order to provide load for the turbogenerators as they are successively started and synchronized and to build up the fires in the boilers it would be necessary at this point to begin re-energizing 25-cycle and 60-cycle feeders supplying radial load only. This would permit adding load in convenient amounts and would fully restore the large traction load supplied from the 25-cycle system, restore all of the 60-cycle load in Westchester County, and partially restore 60-cycle radial load in the outlying areas in the boroughs of Bronx and Brooklyn. At the time of the system peak in 1939 the total amount of radial load thus restored would be approximately 260,000 kilowatts or about 15 per cent of the total system load.

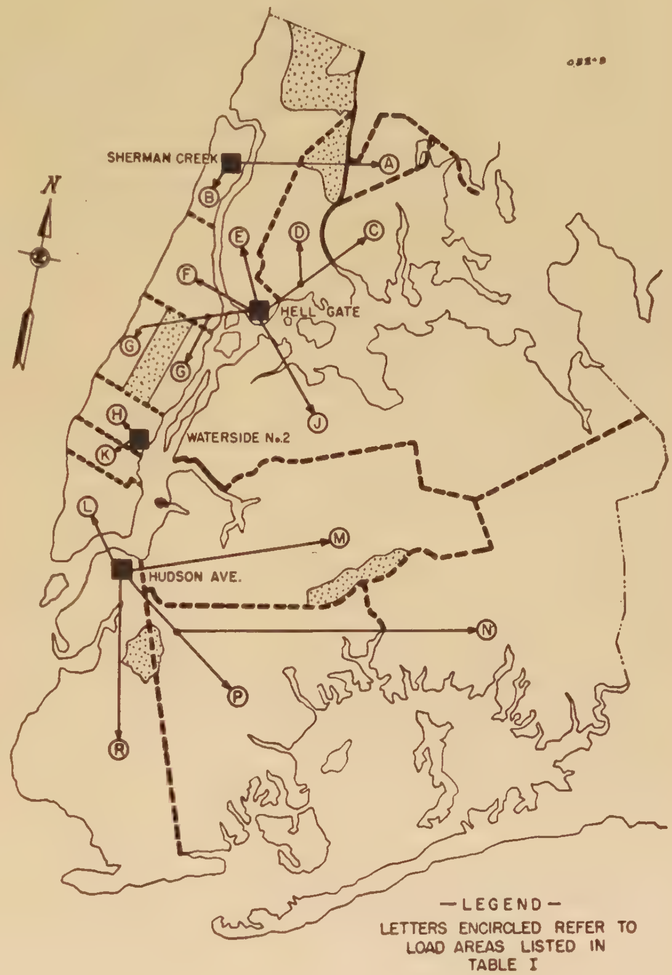


Figure 3. Segregated 60-cycle load areas in New York City

With this amount of load divided among the generating stations it would be possible to restore the 60-cycle networks to service, beginning with the areas having the smallest load and finishing with the largest networks, in each case using the method of restoration to be described later in this paper.

After all of the 60-cycle networks have been restored it would be possible to restore additional 60-cycle radial load amounting to over 200,000 kw which is supplied from feeders which also supply the network load or which is dependent upon the re-energizing of the network load itself. An important 60-cycle load is that of the municipal rapid-transit system in which most of the conversion units are rectifiers and require a supply of auxiliary power from the network before the traction load can be restored. Normal train movements are dependent upon supply from the network for track signals.

The restoration of substantially normal supply to the 60-cycle radial and network loads and to the 25-cycle radial load would build up the total load on the interconnected generating stations to the point where the boiler steaming rates should be high enough to permit the addition of the large block of load represented by the d-c network in Manhattan as the final step in restoring normal service. At the time of the system peak the load on this network is about 375,000 kilowatts and represents about 28 per cent of the total load in the remainder of the system.

The general method of re-energizing each of the 60-cycle networks may be summarized briefly as follows:

1. After the generating station busses have been re-energized, the direct tie feeders between generating stations have been restored, and the frequency changers synchronized, at least one turbogenerator is synchronized to the bus in each station.

2. While additional generators are being started, small blocks of radial 25- and 60-cycle load are connected successively to the busses in each station by re-energizing individual radial feeders as rapidly as consistent with the increase in capacity as the available boiler output is increased. This process is continued until all of the available load has been re-energized except that which would require special switching operations in the field to separate it from network load in the case of feeders supplying both kinds of load.

3. The overcurrent protective relays on all of the 60-cycle tie feeders between generating stations are made inoperative temporarily to prevent them from tripping unnecessarily on the surges which occur as the larger blocks of network load are re-energized. The d-c control supply feeders in the generating stations are paralleled if necessary to insure an adequate supply of control energy for the simultaneous closure of the requisite number of network supply feeders.

4. In a 60-cycle station supplying one or more of the smaller network areas having peak loads ranging from 40,000 kw to 80,000 kw the 60-cycle generator load is increased until as much power as possible is sent out of the station over the 60-cycle ties and through the frequency changer, if any, to the 25-cycle system. The 60-cycle bus voltage will then be raised about five per cent above the normal scheduled value in order to compensate approximately for the increased excitation required for the block of load to be added since automatic voltage regulators are not used. The generating-station switchboard operator will notify the boiler-room engineer immediately before a group of network supply feeders is re-energized so that the boiler room operating force will be prepared to make any adjustments necessary as the load is picked up.

5. The feeder circuit breakers controlling the feeders to the network area selected are closed simultaneously by several operators acting in unison.

6. Immediately after a block of network load is re-energized the load on the generators in the station at which the operation was performed is adjusted manually so that about half of the load added is carried on these generators and the remainder is carried on the generators in other parts of the system through the ties and frequency changers. The bus voltage is adjusted to the normal scheduled value after a block of network load is added unless the same station is to prepare for the immediate addition of another block of load.

This method of re-energizing a typical block of network load is based upon the assumption that the entire Consolidated Edison electric system has been shut down and is to be re-energized with all stations and substantially all parts of the distribution system intact and available for service. In any actual case of shutdown it is unlikely that more than one station will be seriously affected. It is possible, however, that the affected station will have to be restored to service and its load re-energized while one or more of the bus sections are damaged, or while one or more of the main turbogenerators is unavailable for service. All such situations present special problems which require slight changes in the general plan presented.

One of the most important deviations from the general plan would be encountered in the case where a generating station having adequate generating capacity available to carry the normal load might have to be started from a shut-down condition at a time when the 60-cycle ties to other stations were not available for assistance in re-energizing the networks.

While this is a rather remote possibility because the number of separate 60-cycle tie feeders to adjacent stations provided ranges from two to nine and all but one of the stations supplying network load has a connection to the 25-cycle system through one or two large frequency changers we believe that the isolated station would have no particular difficulty in re-energizing the networks it supplies in the following manner:

1. Re-energize all of the available radial load as in the general case and, if necessary, block open the relatively few network protectors at distribution banks connected to dual-purpose feeders which can then be re-energized to restore substantial amounts of additional radial load.

2. Immediately before re-energizing the first and smallest block of network load raise the steam output from the boilers and the steam pressure until steam is discharged from the safety valves. The supply of make-up water is normally adequate for such operation in any of the stations.

3. Re-energize the first block of network load and restore steam pressure to normal if it has dropped to a point below normal.

4. Repeat this process as each block of network load is added, leaving the largest blocks of load to be re-energized last.

Under some conditions it would be feasible to restore service to all or nearly all of the 60-cycle load supplied from a generating station while all of the generators were temporarily unavailable for service because of some condition affecting all of the essential auxiliaries. Such a condition occurred in one instance under circumstances outlined below.

Operating Experiences

The only actual experience obtained in re-energizing segregated 60-cycle load areas in the Consolidated Edison system was on the occasion of the shutdown of the Hell Gate generating station on September 21, 1938, shortly after the work was completed in segregating the load areas supplied by this station. This shutdown was the result of a tidal flood accompanying a hurricane which passed close to New York City on that date. The re-energizing of the areas affected was successfully carried out by following as closely as practicable the methods outlined above. The salient features of this experience were:

1. The shutdown of all 25-cycle and 60-cycle generators in the station was forced by loss of steam pressure following the partial or complete submersion of nearly all of the essential auxiliaries and the complete interruption of the power supply for the auxiliaries which are electrically driven.

2. The 11-kv 25-cycle busses, 13-kv 60-cycle busses, and the associated switchgear were not damaged although all supply to the 60-cycle busses was interrupted because of overloads on the tie feeders and the frequency changer.

3. The shutdown occurred about $1^3/_4$ hours after the time of the system load peak for the day at which time the system load normally is declining at a rate of approximately ten per cent per hour.

4. All 60-cycle service in the north half of the borough of Manhattan and all service in the borough of Bronx and county of Westchester were interrupted. This load amounted to about 360,000 kilowatts.

5. About one-quarter of the interrupted load was restored within six minutes. Service in the remainder of the affected area was restored in several stages over a period of $5^3/_4$ hours. Since none of the generators at Hell Gate station was available for operation for several days after the shutdown, 60-cycle power obtained principally from the Niagara-Hudson system was utilized in restoring service.

6. No difficulty was experienced in re-energizing the networks. The largest block of load re-energized in one operation was 90,000 kilowatts which included all of the load in Westchester County and a small section in New York City. This load was re-energized six minutes after it was interrupted and the load picked up was about equal to the load dropped. The next largest block of load was that of one of the networks in Manhattan. This network was re-energized 41 minutes after the interruption occurred and increased the load on the Niagara-Hudson tie by 30,000 kilowatts which was almost exactly the amount of load in the area at the time of the interruption. A few minutes later another of the Manhattan networks was re-energized but the load increment was only 28,000 kilowatts, about 30 per cent less than the load in that area at the time of the interruption. This reduction of load was partly accounted for by the fact that the service voltage in the areas restored was from 8 to 18 per cent below normal immediately after the second block of network load was added. Seven minutes later, after excitation had been adjusted in the Niagara-Hudson system, the service voltage in the re-energized areas was sufficiently improved to permit re-energizing a third block of network load in New York City with the same effect on load and volt-

age as before. The remaining networks were re-energized shortly thereafter with increased 60-cycle power supply available from other generating stations in New York City over tie feeders which could not be restored earlier because of a system ground fault condition requiring several hours to localize and eliminate.

7. It was found entirely practical to close from 6 to 11 feeder breakers at the generating station in such a manner as to re-energize each network without causing network protector fuses to blow because of temporary local overloads. In the case where 11 breakers had to be closed they were closed in two groups of 6 and 5 respectively by several operators working together.

On the occasion of the shutdown of Hell Gate station the circumstances were such that no experience was obtained in re-energizing large blocks of load with power supplied principally by the generators in the station affected.

However, an indication of the probable effect of re-energizing a large block of load from a given generating station, under conditions where the interconnections among all of the generating stations are operating normally, may be obtained from actual experience in several cases where automatic tripping of transmission-line breakers in the Niagara-Hudson system have resulted in instantaneous increases of 100 to 150 megawatts in the load on the Consolidated Edison system.

In all cases the increased load has been picked up by the interconnected stations in New York with slight effect on the system frequency and voltage.

The largest of these instantaneously applied loads on record occurred at a time when the Consolidated Edison system was receiving 150 megawatts from the Niagara-Hudson system and a bus fault in a substation located near the boundary between the two system territories caused the transmission lines to open at that point. At that time the total generator load in the Consolidated Edison system was 789 megawatts of which about 60 per cent was 60-cycle generation. The instantaneous load increase of 150 megawatts was imposed upon the system through connections to the 60-cycle busses in the Hell Gate and Sherman Creek stations but was shared by all of the interconnected stations with a momentary decrease in frequency of one-half cycle and a voltage dip of from $2^1/_2$ to 9 per cent in various parts of the system. The system frequency was restored to normal within three minutes. Unfortunately there is no complete record of the magnitude of the load increase at each of the generating stations. None of the tie feeders or frequency changers tripped out.

In this case the sudden increment of load represented 19 per cent of the previous load on all generators, 32 per cent of the load on the 60-cycle generators alone, 11 per cent of the total running generator capacity, 79 per cent of the running frequency-changer capacity, and approximately 11 per cent of the total net hot boiler capacity.

The boiler equipment in these stations includes a wide variety of types among which are stoker-fired boilers with and without automatic combustion control and pulverized-fuel installations of the unit-mill type and of the bin type.

The operating experiences mentioned indicate that no particular difficulty should be encountered in re-energizing the largest blocks of network load contemplated under the present design objectives provided that substantially normal tie-feeder and frequency-changer capacity is available for service at the time.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

The Co-ordination of Electrical Equipment With Basic Insulation Levels

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BASIC insulation levels have been defined, and a list of proposed values has been determined by national committees charged with this responsibility. The purpose of this paper is to discuss some of the principles useful in selecting electrical equipment conforming to the requirements of that basic insulation level necessary to assure satisfactory service while operating within the voltage range and under the system conditions expected.

Since the lowest-allowable basic insulation level is closely associated with the protected level provided by the surge-limiting or surge protective equipment, and since the rating of protective equipment selected is closely associated with values of system operating voltage to ground, it is evident that there exist interrelations among:

A. Voltages expected to exist on the electrical system

(*a*). Low frequency or dynamic

(*b*). Surge

B. Voltages permitted by surge protective devices

C. Basic insulation levels

D. Insulation strengths of electrical equipment

The latest proposed values for basic insulation levels are being reported to the Institute by representatives of the national committees having these matters in hand.[1] The performance of lightning-surge protective devices and other related matters also are being presented in associated papers before the Institute.[2,3]

Operating Requirements of Apparatus Insulation

It is of interest to examine the relations existing between required insulation strengths and service conditions on operating systems. Apparatus must be designed to withstand satisfactorily a variety of voltages imposed upon it. Such voltages include:

A. Continuously applied low-frequency voltage

(*a*). Between terminals

(*b*). Between live parts and ground

B. Occasionally applied low-frequency overvoltages

(*a*). Between terminals

(*b*). Between live parts and ground

C. Occasionally applied inpulse overvoltages between live parts and ground

The basic insulation level as now de-

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1. For all numbered references, see list at end of paper.

fined directly refers only to the last of these varieties. A study of the relationships which should exist between this characteristic and the others is essential to the successful co-ordination of the design characteristics of electrical equipment with basic insulation levels. In the past, it has been common practice to relate insulation strengths to the rated continuous low-frequency voltage *between terminals* for which the apparatus was designed. However, a study of the considerations enumerated above leads to the conclusion that insulation strengths more properly should be related both to (*a*) the surge voltages, and (*b*) the continuous dynamic voltages expected to exist *between live parts and ground.*

A fundamental requirement of apparatus insulation is that its strength between live parts and ground shall be at least equal to the maximum voltage expected to occur between live parts and ground. In the case of impulse surges this maximum value may be considered to be the "protected level" provided by the associated protective apparatus. Therefore, that basic insulation level which is equal to or in excess of the established "protected level" would be the minimum insulation level applicable to the apparatus in question.

As discussed rather completely in a former paper,[4] the protected level must be placed sufficiently above the expected performance of the protective device to provide a reasonable margin which will insure the integrity of the protected level. This margin must take into account many factors, including manufacturing tolerances, layout and arrangement of the station, vagaries of surges and protective equipment, assurance of selective operation of the protective device, etc.

Table I. Typical 4,160-Volt Wye Substation

Insulation Design Basis: Basic Insulation Level 60 on Bus and Important Apparatus; 45 Elsewhere

Item	Apparatus Insulation Classification* (Kv)	Voltage Rating* (Kv)	Withstand Voltage: Low-Frequency Test (Kv RMS)	Withstand Voltage: Impulse Full-Wave Test (Kv Crest)
Surge protective equipment:				
Lightning arrester		3		
Supply transformers:				
(Over 500 kva)	5	2.4/4.16 wye	19	76
Station power transformers:				
(Less than 500 kva)	5	2.4/4.16 wye	19	60
Regulators:				
(Under 750 kva, three phase)	5	4.16	19	60
Instrument transformers:				
Current, indoor on bus	8.7	8.66	19	60
Potential, indoor on bus (ratio 20 to 1)	8.7	2.4	19	60
Current, on feeder	5	5	15	50
Potential, on feeder	5	5	15	50
Oil circuit breakers:				
Indoor (below 500,000 kva)	7.5	7.5	19	60
Bus and switch insulators		7.5†		85**
Bushings:				
Outdoor	5		24 wet	75
Indoor	7.5		25 dry	60
Synchronous condenser	7.5	4.16	16	

* This designation is that at present used by manufacturers.

† Lowest standard rating.

** Flashover rating. Impulse withstand test not yet determined.

Basic Insulation Levels

The present accepted definition of "basic insulation levels" is as follows:

"Basic impulse insulation levels are reference levels expressed in impulse crest voltage with a standard wave not longer than a $1^1/_2$x40-microsecond wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic insulation level."

For many years, insulation levels have been defined, perhaps inadequately, in terms of test voltages impressed for a period of time at low frequencies. The basic insulation levels under discussion, however, are defined in terms of impulse voltages with no mention of low-frequency or sustained-voltage strengths. The definition contemplates that apparatus shall withstand successfully the imposition of surges having values as great as the basic insulation level for which the apparatus was designed.

The basic-impulse-insulation-level values most recently proposed, as given in the joint committee report, "Basic Insulation Levels"[1] by Messrs. Powel and Sporn, are as follows:

Proposed Basic Insulation Levels, Impulse Crest Kilovolts

30	150	650
45	200	750
60	250	900
75	350	1,050
95	450	1,300
110	550	1,550

This list of values constitutes a schedule of insulation impulse strengths to ground which may be made available in apparatus of voltage ratings as required by the trade. It is of interest to examine the relationships existing between service conditions on operating systems and the corresponding insulation levels required for apparatus.

Procedure for Selection of a Particular Basic Insulation Level

Since the selection of basic insulation levels is closely associated with the performance of the protective devices which in turn are selected on the basis of maximum dynamic voltages expected to exist at the point of application, the first consideration in selecting a basic insulation level is to determine the maximum operating voltages between conductors. Next, the system connections and the neutral stability must be considered in order to determine the maximum dynamic voltages between conductors and ground under fault conditions. These values lead immediately to the selection of the voltage rating of the protective device, since the low-frequency characteristics of this device must be co-ordinated with the voltages expected to exist between lines and ground. During line-to-ground faults, the voltage on the faulted phase decreases and the voltage between the unfaulted phases and ground generally increases. The magnitude of the voltage between the unfaulted phases and ground will depend upon the system electrical characteristics and the type of fault and will usually exceed the normal line-to-neutral voltage. Under some circumstances, it may exceed the normal line-to-line voltage. The procedure to be followed in calculating these voltages is adequately covered in other papers which have been presented before the Institute and elsewhere.[5,6,7]

Due to the inherent nature of surge protective devices, they have a maximum voltage rating (given in manufacturers' publications and references)[8–12] which is a measure of the maximum dynamic voltage which may be applied to them during fault conditions. There is always a possi-

bility that the protective devices may be surged simultaneously with the fault. Therefore, the maximum voltage between unfaulted phases and ground which can occur at the point of installation is of prime importance in the application of the protective device, and the voltage rating must be determined in conjunction with the type of grounding as well as with the line-to-line system operating voltage.

A study of the characteristics of the protective device under assumed surge conditions, together with provision for a suitable margin, leads immediately to the protected level which will be provided.

Messrs. Sporn and Gross, in their paper, "Rationalization of System Insulation III—Margins Between Basic Insulation Levels and Protected Levels",[3] suggest that a value given by the formula: (0.10× arrester maximum performance)+25 kv, provides a margin which is generally suitable for the conditions usually to be expected. Margins as calculated by this formula are used in the illustrative examples given later in this paper. Engineering consideration of the specific conditions involved may lead to the requirement for different margins in other cases.

For apparatus closely and continuously associated with a protective device, the basic insulation level equal to or just above the protected level thus determined would probably be the minimum to which the apparatus must conform. In certain situations, the importance of service as related to the economics of the application may indicate the wisdom of selecting a higher or lower basic insulation level.

In stations accommodating many connecting lines and in stations of considerable extent, it may be that different types of protective devices are used at different locations; also, the operation of switching equipment may isolate certain apparatus from some of the protective devices. Therefore, it may be that some of the apparatus in the station should be designed to operate with a different protected level and, consequently, a different basic insulation level than other apparatus in the same station.

The impulse characteristics of a particular piece of apparatus and the corresponding characteristics of the protective device must be studied to assure that an adequate margin is being provided between the protected level and the insulation strength of the apparatus at all points on its volt-time curve.

Co-ordination based on insulation levels as determined by full-wave "withstand" voltage tests is satisfactory only when the protected level is relatively flat down to very short time on the volt-time curve.[4] This is practically true for modern lightning arresters where the short-time protected level is determined by the gap breakdown plus suitable tolerance and margin, and the longer-time protected level comparable to the full-wave test on apparatus is determined by the IR drop at some specified value of discharge current plus suitable tolerance and margin. If a gap type of protective device such as a protector tube or a plain rod gap is to be used, the protection afforded is based entirely on the time to break down and should not be considered as a level, but rather a volt-time curve. In this case, a comparison of the apparatus chopped-wave impulse-voltage test with the gap breakdown at a comparable time plus suitable tolerance and margin would more accurately represent co-ordination for apparatus on which complete volt-time curves are not available.

In selecting the insulation level for a specific situation, consideration should be given to the requirements as imposed both by the low-frequency voltages and the impulse voltages which may exist. This discussion deals principally with the impulse voltages. However, the low-frequency voltages which may appear on the system must also be given adequate consideration and the low-frequency insulation requirements, both dry and wet, determined with evaluation of specific conditions, such as dirt, condensation, fog, etc. *In the final analysis, the insulation suitable for a given situation will be that which fulfills the low-frequency requirements, the surge-voltage requirements, and the economics involved.*

Illustrative Examples

In order to make more clear and specific the application of this procedure to the selection of impulse levels, three examples are outlined below. It is thought that the conditions selected are those typically existing on many large transmission and distribution systems in the United States. For convenient reference, table IV summarizes the present impulse insulation levels of various types of apparatus listed according to the impulse full-wave voltage-test levels. These data are based on information available at the present time.

Example I—Typical Low-Voltage Distribution-Substation Apparatus

Assume a 4,160-volt distribution substation with bus and switching equipment indoors, transformers and regulators outdoors, and with overhead lines connected. The supply transformers are all to be connected wye on the low-voltage side with the neutral solidly grounded and delta connected on the high-voltage side. This makes the ratio X_0/X_1 less than one at all times and, therefore, under fault conditions the voltage to ground at the substation will not exceed normal maximum line-to-ground operating voltage[5,6,7] which might be as high as 2,800 volts on the line side of the voltage regulators. This allows the use of 3-kv protective devices for the supply transformers, the bus, or the regulators. Allowing a margin of ten per cent above the arrester maximum performance at 5,000 amperes discharge

Table II. Typical 12,000-Volt Substation

Designed for Basic Insulation Level 95

Item	Apparatus Insulation Classification* (Kv)	Voltage Rating* (Kv)	Withstand Voltage: Low-Frequency Test (Kv RMS)	Withstand Voltage: Impulse Full-Wave Test (Kv Crest)
Surge protective equipment:				
Lightning arrester		12		
Supply transformers:				
(Over 500 kva)	15	12	34	112
Station power transformers:				
(Less than 500 kva)	15	12	34	95
Regulators:				
(Less than 750 kva, three phase)	15	12	34	95
Instrument transformers:				
Current, outdoor	15	15	34	95
Potential, outdoor (ratio 100 to 1)	15	12	34	95
Current, indoor	25	25	34	95
Potential, indoor (ratio 100 to 1)	Special	12	34	95
Oil circuit breakers:				
Outdoor	15	15	54	110
Indoor—Below 500,000 kva	15†	15†	36†	80†
Bus and switch insulators		25	63* wet	145**
Bushings: Outdoor	15		45 wet	110

* This designation is that at present used by manufacturers.

** Flashover rating. Impulse withstand test not yet determined.

† Available indoor apparatus does not meet basic-insulation-level requirements. Next higher (23 kv) rated breakers are at present available only in ratings 500,000 kva and above.

plus 25 kv and using the "industry characteristics" for a modern 3-kv line-type arrester,[10] the protected level would be 44 kv (17.5+1.7+25=44 kv) and the minimum allowable basic insulation level would thus be 45 kv for apparatus closely connected to the protective devices. However, if the station is large or important, a higher basic insulation level probably is justified for apparatus in the most important locations, and a 60-kv basic insulation level would then be indicated for bus and switch insulators, power transformers, circuit breakers, and other apparatus whose failure would mean a complete station interruption.

The selection of the specific apparatus is next a matter of determining the rating or type designation of each kind of apparatus which will meet the impulse insulation level and the low-frequency requirements as decided upon. Table I illustrates a typical selection of equipment for the 4,160-volt distribution substation of example I as based on present available insulation classes necessary to meet a 60-kv, or 45-kv impulse level where such would be permissible. It will be noted that there is little consistency among the various designations of apparatus insulation classes as related to the impulse full-wave test values for the different types of apparatus. The potential transformers connected to the bus would probably be special, since the present practice is to make 20/1 indoor potential transformers to the 50-kv impulse level. If the potential transformers were connected through an adequately insulated fuse and used only for such purposes that a failure of a potential transformer would not cause an interruption, the 50-kv impulse level probably would be considered satisfactory.

It will be noted that low-frequency test values are also included in table I. As mentioned above, consideration must be given to low-frequency requirements in selecting apparatus. However, further analysis of these requirements is not given here since it is outside the scope of this paper.

Example II—Typical High-Voltage Distribution-Substation Apparatus

Assume a major switching substation including indoor and outdoor apparatus operating at 12,000 volts. The station contains disconnecting switches, oil circuit breakers, voltage regulators, potential and current transformers, and stepdown transformers connected delta. The power supply comes in over several overhead lines, the oil circuit breakers to some of which at times may be operated open and to which potential transformers are connected on the line side in connection with the automatic switching scheme contemplated.

Following the outline of example I, it is determined that the low-frequency line-to-line voltage may reach 13,000. The neutral is not effectively grounded, since the neutral ground is located at the generating station some distance away and the maximum low-frequency line-to-ground voltage is accordingly determined to be 11,000 volts. This will require the use of 12-kv-rated protective devices. With line-type arresters for installation on incoming lines and power transformers, a protected level of 94 kv (62.5+6.2+25=94 kv) would be provided and a basic insulation level of 95 kv would be suitable for the impulse requirement of all apparatus in this station. The low-frequency wet voltage requirements would also have to be investigated in the final selection of porcelain insulation, since this wet requirement frequently is the determining factor in this class of substation and may provide a higher impulse characteristic than indicated by the basic-insulation-level requirement.

It will be seen from the values in table II that for bus insulators and indoor instrument transformers, it is necessary at present to select some equipment having a voltage rating of 25 kv in order to meet the insulation requirements and co-ordinate with the other apparatus. In the case of circuit breakers, the existing indoor types having interrupting ratings below 500,000 kva have impulse full-wave test values considerably below that of the other apparatus. Breakers of this interrupting rating are not generally available in the next higher voltage (23 kv) class.

Example III—Typical High-Voltage Substation Apparatus

Assume a 138-kv transmission substation in connection with a steam generating plant. The step-up transformers, of which there are two banks, are delta-connected on the generator side and wye-connected on the high-voltage side with the neutral solidly grounded. One of the transmission lines is an interconnection with another system and therefore has metering and regulating equipment on the line side of the breaker.

Following the procedure outlined, the possible dynamic overvoltages are analyzed at:

(*a*). The transformer connections—where it is desired to install a lightning arrester as close to the transformers as practicable

(*b*). The bus—to which it is considered that one transformer bank will always be connected

(*c*). The line sides of all breakers and metering equipment

Table III. Typical 138-Kv Substation

Insulation Design Basis: Basic Insulation Level 650 on Incoming Lines; 550 Elsewhere

Item	Apparatus Insulation Classification* (Kv)	Voltage Rating* (Kv)	Withstand Voltages: Low-Frequency Test (Kv RMS)	Withstand Voltages: Impulse Full-Wave Test (Kv Crest)
Main bus and transformers				
Surge protective device:				
Lightning arrester		121 (109)		
Power transformers	115	138	231	540
Instrument transformers:				
Potential (ratio 1,200 to 1)	115	138	231	540
Current	115	115	231	540
Oil circuit breakers	138†	138†	313	680
Bus and switch insulators		115	255 wet**	550**
Bushings		115	230 wet	550
Line connections				
Surge protective devices:				
Lightning arrester		145 (133)		
Line entrance gap		35 in.		
Regulating equipment	138	138	277	650
Instrument transformers:				
Potential (ratio 1,200 to 1)	138	138	277	650
Current	138	138	277	650
Oil circuit breakers	138	138	313	680
Bus and switch insulators		138	340 wet**	705**
Bushings		138	275 wet	650

* This designation is that at present used by manufacturers.

() The greater margins between the protected level and the basic insulation level provided by these lower ratings may be utilized where applicable.

† Line-to-line voltage requirements determine the rating of this apparatus.

** Flashover rating. Impulse withstand tests not yet determined.

Table IV. Present Impulse Insulation Levels of Apparatus

Apparatus Full-Wave Test—$1^1/_2 \times 40$-Microsecond Crest Kilovolts

Manufacturer's voltage classification	2.5	5	7.5/8.7	15	25	34.5	46	69	92	115	138	161	196	230	287	345
Transformers over 500 kva		76	95	112	153	195	245	345	445	540	645	750	900	1,050	1,290	1,540
Transformers 500 kva or less	50	60	76	95	153	195	245	345	445	540	645	750	900	1,050	1,290	1,540
Step regulators:																
Over 250 kva, single phase; Over 750 kva, three phase		76	95	112	153	195	245	345	445	540	645	750	900	1,050	1,290	1,540
Step regulators:																
250 kva or less, single phase; 750 kva or less, three phase	50	60	76	95	153	195	245	345	445	540	645	750	900	1,050	1,290	1,540
Transformers—instrument—outdoor	50	60	76	95	153	195	245	345	445	540	645	750	900	1,050	1,290	1,540
Transformers—instrument—indoor**	30	50	60	76												
Induction regulators (proposed)	Same as step regulators															
Outdoor bushings (proposed for all apparatus rated above 15 kv, and major apparatus 15 kv and below)	60	75	95	110	150	200	250	350	450	550	650	750	900	1,050	1,300	1,550
Indoor bushings	30	45	60	75	130	180										
Insulators—switch and bus*			85	110	145	190	230	315	350	550	705	705	880	1,045		
Oil circuit breakers:‡																
Outdoor—50,000 kva and up			75	110	150	190	250	360	470	570	680	790	950	1,100	1,360	1,620
Indoor—50,000 kva—500,000 kva			60	80												
Indoor—500,000 kva and up				95	110	150										
Synchronous machines†	7.0	13	21	41												

* Mininum average impulse flashover ratings $1^1/_2 \times 40$ wave. Withstand (full wave) voltage values now being established.

†Not impulse test value. Required protected level = 1.4 (2×rating+1 kv).

** In some ratings higher insulation levels are available.

‡ Negative five per cent tolerance allowable for "withstand" basis.

With the transformers solidly grounded at all times, the condition for maximum dynamic line-to-ground voltage is found to be with maximum system generation and with one transformer bank in service. This voltage is calculated to be 100 kv to ground, which allows the use of lightning arresters rated 121 kv or even 109 kv on the transformers or the bus. The basic insulation level selected for the transformers and bus is, therefore, 550 kv[3,4,8] based on a protected level of 463+46+25=534 kv.

It is found by calculation that the maximum low-frequency voltage on the line side of the various breakers may be greater than that considered satisfactory for 121-kv protective devices and, therefore, 145-kv or at least 133-kv protective devices are required with a corresponding basic insulation level of 650 kv. All this is shown in table III.

Conclusions

1. The maximum dynamic *line-to-ground* voltage of the operating system existing at the apparatus under consideration is largely determinate in the selection of the basic insulation level required of that apparatus.

2. In selecting apparatus from the standpoint of its insulation strength, it is necessary to consider the insulation test levels to which the apparatus is designed, taking into account both the low-frequency and the impulse levels rather than merely the manufacturer's voltage rating.

3. The insulation strength of all types of apparatus should be clearly designated on the name plate in terms of the "low-frequency withstand" and "impulse withstand" voltage levels.

4. Analysis indicates that the schedule of basic insulation levels provided is adequate to fit the variety of requirements usually to be expected.

5. The basic insulation levels required of certain apparatus closely coupled and continuously associated with the protective device is not necessarily the same as that required of other apparatus in the same station which does not have the same degree of protection; for instance, power transformers as compared with line entrance switches or line potential transformers.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Proposed Standards for Outdoor Bushings

AIEE JOINT COMMITTEE ON BUSHINGS

THE electrical characteristics of bushings for different types of apparatus vary considerably for corresponding voltage ratings. This is partly due to the fact that different committees have handled the preparation of standards for different types of apparatus. Consequently the AIEE joint committee on bushings was formed in an effort to develop more consistent standards covering the electrical characteristics of bushings for all types of apparatus.

The joint committee was formed in February 1938 under the sponsorship of the AIEE standards committee. Its membership includes representatives from the three AIEE technical committees which deal with bushings, namely, the electrical machinery committee, power transmission and distribution committee, and the protective devices committee. The membership was carefully selected to provide tie-ins with the Edison Electric Institute-National Electrical Manufacturers Association Joint Committee on Co-ordination of Insulation and other committees interested in this problem.

Two major questions are involved in this problem, one, what electrical characteristics are required to meet conditions encountered in service and, two, how nearly do present-day bushings meet these requirements? Two subcommittees were formed to deal with these two questions separately. It was apparent that it would be necessary to prepare definitions and a test code and two other subcommittees were formed to prepare these.

In an effort to determine the requirements on an engineering basis a preliminary tabulation was prepared. The low-frequency characteristics were chosen to provide a satisfactory margin of insulation strength for overvoltages due to switching surges, overspeed, fault conditions, etc. The impulse characteristics were chosen to provide a satisfactory margin of insulation strength above the level of lightning protection which can be provided with modern lightning-protection equipment. The impulse characteristics selected are in accord with the values being considered by the Joint Committee on Co-ordination of Insulation. It was agreed that all of these characteristics should be expressed in terms of "withstand voltages" rather than "flashover voltages" in order to eliminate the variations and uncertainties involved in flashover tests.

Table I. Proposed Standards for Outdoor Bushings

Recommended Minimum Withstand Test Voltages

Voltage Classification (Kv)	Low-Frequency Test, RMS Kv: 1 Min. Dry	Low-Frequency Test, RMS Kv: 10 Sec Wet	Impulse Test, $1\frac{1}{2}$ x 40-μ Sec Full Wave (Positive or Negative) (Whichever Is Lower) (Crest Kv)
2.5	21	20	60
5.0	27	24	75
8.7	35	30	95
15.0	50	45	110
23.0	70	60	150
34.5	95	80	200
46	120	100	250
69	175	145	350
92	225	190	450
115	280	230	550
138	335	275	650
161	385	315	750
196	465	385	900
230	545	445	1,050
287	680	555	1,300
345	810	665	1,550

Explanatory notes:

1. These test values apply to outdoor bushings for all types of apparatus in the voltage classifications 23 kv and up.

2. For voltage classifications 15 kv and below, the test values apply to bushings for major apparatus such as large oil circuit breakers, power transformers, etc.

3. Lower test values may be assigned for bushings used for small oil circuit breakers, distribution transformers, etc. Further study is being given this phase of the subject by the committee.

Other tabulations were prepared independently showing the characteristics of present-day bushings and these values were compared with the requirements as mentioned above.

After considerable study of these two tabulations the following recommendations for outdoor bushings have been agreed upon by the committee:

Fundamental Principles

(*a*). Bushings are generally integral parts of apparatus, but for the purpose of this study they are considered as separate items of equipment.

(*b*). Performance requirements of bushings shall be such as to permit standard tests on the apparatus with which they are used.

(*c*). Performance requirements are given on the basis of bushings without horn gaps, and under standard atmospheric conditions.

(*d*). Bushings are not intended as protective devices, although they may incidentally furnish partial protection to the apparatus upon which they are installed.

(*e*). The electrical strength characteristics are defined in terms of "withstand" test voltages.

(*f*). In all designs of bushings, the puncture voltage shall be greater than the flashover voltages for both 60-cycle and impulse waves under all standard test conditions.

Performance Requirements

Bushings shall be suitable for operating at their standard ratings:

(*a*). When and where the temperature of the cooling medium does not exceed 40 degrees centigrade.

(*b*). Where the altitude does not exceed 3,300 feet (1,000 meters).

The bushing requirements as specified in table I apply to outdoor bushings when mounted for testing in accordance with a specified arrangement yet to be determined in the test code.

Withstand Test Voltage

Withstand test voltage is the specified test voltage to be applied under specified conditions without bushing flashover.

For low-frequency voltage the values are expressed as root mean square for a specified time.

For impulse voltages the values are expressed as the crest of a specified wave of either positive or negative polarity, whichever gives the lower value. The impulse voltage shall be applied three times, and if any one (not more than one) of these three applications causes flashover, then the series of tests can be repeated. If in the second series of tests no flashover occurs, then the test causing flashover shall be considered a random shot and disregarded.

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Personnel of AIEE joint committee on bushings: R. T. Henry, chairman; F. S. Brown, J. E. Clem, I. W. Gross, L. H. Hill, J. T. Lusignan, A. C. Monteith, J. R. North, E. Piepho, M. S. Oldacre, A. J. A. Peterson, R. E. Pierce, C. B. Springer, P. C. Turk, F. J. Vogel, and L. Wetherill.

Rationalization of Transmission-System Insulation Strength—III

Margins Between Basic Insulation Levels and Protectable Levels

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SINCE the subject of "Rationalization of Transmission-System Insulation Strength"[1] was first presented in a comprehensive manner in 1928, a great deal of constructive study and analysis have been devoted to the problem, and outstanding progress has been made in placing the insulation of an electric system on a more rational basis from the lightning or impulse viewpoint. Three groups have been most active in this work; the equipment manufacturers, the laboratories, and the users of equipment. Particular attention has been given by the manufacturers to increasing and protecting the impulse strength of various types of commercial apparatus. The laboratories have worked on obtaining fundamental impulse data on equipment impulse strength, and have set up approved methods of testing. Both the above groups as well as the users of equipment have co-operated in field investigations to determine the characteristics of natural lightning. Finally, the users, in co-operation with both the other groups, have worked untiringly to co-ordinate the entire work into a rationalized insulation system. This principle of insulation rationalization should not be lost sight of in the individual or group efforts on insulation co-ordination to develop particular equipment to meet definite impulse strengths. That is, the fundamental problem is one of rationalizing system insulation strength by co-ordinating the insulation strength of the various items of equipment constituting or forming a part of the transmission or distribution system.

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1. For all numbered references, see list at end of paper.

Summary

The AIEE joint committee on bushings has attempted to determine the electrical characteristics of bushings on an engineering basis. The recommendations in this report are based on the theory that an ample margin of insulation strength should be provided above the voltages to which the bushings may be subjected in service, including dynamic overvoltages, switching surges, and lightning surges up to the level of protection which can be provided with modern lightning protective devices. This should make it possible to use bushings having the same electrical characteristics for transformers, circuit breakers, and all types of apparatus of corresponding voltage ratings because, if bushings have an ample margin of insulation strength above the level of protection which can be provided, there should be no need for any higher insulation strength for bushings in circuit breakers than in transformers or other apparatus. Lower values of insulation strength may be assigned for bushings for small circuit breakers, distribution transformers, etc., where space or other limitations may require smaller bushings and where a smaller margin of protection may be satisfactory.

The joint committee is continuing the study of bushings and will make additional recommendations covering indoor bushings as soon as agreement can be reached. They may also make recommendations covering bushings for lower-voltage ratings and possibly other characteristics of outdoor bushings.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Principles of Insulation Rationalization and Co-ordination

The general principle of insulation rationalization requires three steps.

1. The setting up of a group of insulation levels which can be assigned to various items of equipment.
2. Establishing steps of insulation strength, as seem reasonable, between various types of equipment to insure electrical breakdown, if it does occur, taking place at a predetermined location.
3. Establishing a reasonable margin between the voltage level held by the protective device (the protectable level) and the various basic levels themselves to insure that adequate protection is provided. It is with this latter consideration that the present paper is primarily concerned.

Co-ordination has too frequently been interpreted to mean bringing into the same order, or equality; so strictly interpreted it might well refer to the process of getting equipment to meet an agreed-upon level. Thus, a common level might be sought for all classes of equipment operating on a grounded 69-kv system, for example. But this attempt at oversimplification of the problem will not help its solution. If a distinction is to be made, then, the problem of deciding what types of equipment for given operating conditions shall have equal insulation, is one of co-ordination. On the other hand the setting up of basic insulation levels and applying the margins between levels and between different equipment in a given voltage class is rationalization.

The establishment of insulation steps between different classes of equipment on a given system is predicated on the assumption that the lower-insulated equipment will fail first, and without resulting in flashover or damage of the higher-insulated member. Likewise, the protective-device level should have a sufficient margin between the basic level (which controls the insulation strength of equipment in that level) to insure that all impulse or surge overvoltages which may reasonably be expected will be definitely limited by the protective device to a value below the basic level or to the values allowed for equipment in that level.

This idea was first proposed in 1928[1] and is as sound today as it seemed and was then. It is recognized, however, that the practical working out of it may be difficult if one of the criteria to be observed is to be the highly desirable one of imposing no undue sharp financial burden on the electrical industry. Hence, it will be necessary to be patient. But it would be a grave error to overlook the importance of getting the principle established as soon

Table I. Determination of Margins of Protection Between Basic Impulse Insulation Levels (BIL) and Protective Devices

All Voltage Values Kilovolts Unless Marked by Asterisk (*) in Column 1

REF.	Column — 1		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
(a)	INSULATION REFERENCE CLASS		0.6	1.2	2.5	5.0	8.7	12	15	23	34.5	46	69	92	115	138	161	196	230	288	345
(b)	SYSTEM VOLTAGE-HIGHEST NORMAL (Phase To Phase)	KV*	0.6	1.2	2.4	4.8	8.3	12.5	14.4	24	36	46	69	92	115	138	161	196	230	288	345
(c)	OPERATING VOLTAGE-HIGHEST EXPECTED (Phase To Phase)	KV*	0.72	1.44	2.9	5.8	10	13.8	16.5	25.8	38.1	48.7	73.1	97.5	122	146	171	208	244	305	366
	ISOLATED NEUTRAL SYSTEM — L.As																				
(d)	L.A. MAX. VOLTAGE RATING (For Isolated Neut. System)	KV*	1	1.5	3	6	12	15	20	25	40	50	73	97	121	145	169	207	242	302	363
(e)	L.A.: IR FOR ISOL. NEUT. SYSTEM	KV(1)	6	9	18/11	33/23	63/46	78/57	94/77	118/95	190/154	238/192	348/282	371	463	560	651	780	927	1160	1400
(f)	MARGIN OF BIL ABOVE ISOL. NEUT. L.A (q-e)	KV(1)	19	21	27/34	27/37	12/29	17/38	16/33	32/55	10/46	12/58	2/68	79	87	90	99	120	123	140	150
(g)	MARGIN OF NEXT HIGHER BIL ABOVE ISOL. NEUT. L.A. [(q+1)-e]	KV(1)	24	36	42/49	42/52	32/39	32/53	56/73	82/105	60/96	112/158	102/168	179	187	190	249	270	373	390	—
	GROUNDED NEUTRAL SYSTEM — L.A.s																				
(h)	SYSTEM FAULT VOLTAGE-LINE TO GROUND (Under Fault Conditions-Effect. Gr. Neut. System)	KV*	0.54	1.06	2.18	4.35	7.5	10.4	12.4	19.3	28.6	36.5	55	73	91.5	110	128	156	183	229	274
(i)	L.A. MAX. VOLTAGE RATING (For Effect. Gr. Neut. System)	KV	1	1	3	6	9	12	12	20	30	37	60	73	97	109	133	157	183	230	277
(j)	L.A.: IR FOR EFFECT. GR. NEUT. SYSTEM	KV(1)	6	6	18/11	33/23	48/34	63/46	63/46	94/77	142/115	176/143	286/230	348/282	371	420	515	605	705	885	1070
(k)	MARGIN OF BIL ABOVE EFFECT. GR. NEUT. L.A. (q-j)	KV(1)	19	24	27/34	27/37	27/41	32/49	47/64	56/73	58/85	74/107	64/120	102/168	179	230	235	295	345	415	480
(l)	MARGIN OF BIL ABOVE EFFECT. GR. NEUT. L.A. IN NEXT HIGHER INSUL. CLASS [q-(j+1)]	KV(1)	19	12/19	12/22	12/26	12/29	32/49	16/33	8/35	24/57	-36/20	2/68	79	130	135	145	195	165	230	—
	ISOLATED OR GROUNDED NEUTRAL SYSTEMS — ROD GAPS																				
(m)	3/4 LINE TO NEUT. VOLTAGE (Based on c)	KV*	1.35	2.7	5.4	10.9	18.7	25.8	31.0	43.8	71.5	91.3	137	183	229	274	320	390	457	572	685
(n)	ROD GAP SPACING (Having 60~ F.O. Given in (m) ½" x ½" Sq. Cut Rod Gap)	IN.	0.07	0.14	0.28	0.55	1.0	1.5	1.9	3.4	6.0	8.5	13.5	18.2	23	27.5	32	40	47.5	60	73
(o)	ROD GAP F.O. (1x5 Neg. Impulse-Avg. Values-50/50 F.O.)	KV	4	7	13	25	37	50	58	92	145	195	300	400	500	600	690	870	1030	1300	1550
(p)	MARGIN OF BIL ABOVE GAP F.O. (q-t)	KV	20	22	30	32	32	37	43	44	33	26	6	-10	-25	-40	-50	-100	-130	-200	-230
	COMPARISON OF BILs WITH L.A. AND ROD GAP CHARACTERISTICS PLUS MARGINS																				
(q)	PROPOSED BASIC IMPULSE INSUL. LEVELS (Crest of 1½x40 Full Wave-Pos. or Neg.)	KV	25	30	45	60	75	95	110	150	200	250	350	450	550	650	750	900	1050	1300	1550
(r)	L.A.: 1.10 IR+25 (For Isolated Neut. System) From (e)	KV(1)	32	35	45/36	61/50	95/76	112/88	128/110	155/130	233/195	287/236	408/335	433	534	641	741	883	1045	1301	1565
(s)	L.A.: 1.10 IR+25 (For Effect. Gr. Neut. System) From (j)	KV(1)	32	32	45/36	61/50	78/62	95/76	95/76	128/110	181/152	219/182	340/278	408/335	433	487	592	691	801	999	1201
(t)	ROD GAP F.O. (1x5 Neg. Impulse-Ref. (o) Plus 15%)	KV	5	8	15	28	43	58	67	106	167	224	344	460	575	690	790	1000	1180	1500	1780

* 60 CYCLE R.M.S. (1) WHERE TWO FIGURES ARE GIVEN THE FIRST IS FOR DISTR. OR LINE TYPE L.A.s – THE SECOND FOR STATION TYPE L.A.s

as technical and industry conditions permit.

Considerations Involved in Insulation Margins

There are a number of important considerations involved in establishing margins between protectable levels and basic levels, or what may be called the safe or withstand strength of the equipment built to that level. Among these are the following which are discussed below:

1. Protective-Device Characteristics

Two factors must be considered in the protective device itself: first, its 60-cycle rating; and second, its protective characteristics. A protective device such as a lightning arrester or, in fact, a protective gap, may be considered to have a 60-cycle rating above which it is generally not considered safe or desirable to operate the device. It is well known that a lightning arrester operated continuously or even for short periods of time with a voltage across its terminals above its rating is subject to failure from dynamic overvoltage. Likewise, a protective gap has a lower limit of permissible setting below which the system to which it is applied, when subject to overvoltages such as switching surges and other transients which are not necessarily dangerous to the system insulation, may experience excessive interruptions, thus preventing the rendering of adequate, not to say high grade, service. The normal-frequency voltage of the system, therefore, determines to a large extent the minimum lightning protection which it is possible to apply.

In considering the protective characteristics of the arrester, a number of factors must be considered, on some of which we have little or no information at the present time. These factors are:

(*a*). The maximum lightning current which the arrester may be called upon to discharge. Considerable progress has been made in obtaining information on the magnitude and frequency of such currents in actual field installations.[2,3]

(*b*). The protective characteristic of the arrester (*IR* drop) varies with the magnitude and rate of current rise through the arrester. The rate of rise of currents through arresters in service is unknown.

(*c*). Again, the lightning-arrester characteristic is affected by the rate of voltage rise of the incoming surge and the arrester-gap breakdown under this condition may be important.

(*d*). A manufacturing tolerance has to be allowed for, as no two arresters of identical characteristics, even made by one manufacturer at the same time, can be relied upon to have exactly the same electrical characteristics.

(*e*). While the arrester may hold the lightning voltage at its own terminals to a predetermined value, under given conditions, just how far distant (circuit feet) it is possible to supply this protection is one of theoretical calculation only at the present time, and again depends upon the rate of voltage rise of the incoming surge and upon voltage reflections.

2. Frequency of Overstress Voltages

The normal or excess margin of insulation over its rated or tested value may have to be taken advantage of in setting up margins between basic and protectable levels. For example, if currents of 15,000 to 30,000 amperes are discharged by the arrester only once in 10 or 20 years, it may be more economical to overstress some equipment insulation once during this period as a result of such a surge, rather than attempt, by expensive additional insulation to maintain the basic insulation

level above this value under such conditions.

3. Effect of Aging or Other Deterioration of Insulation

It is well known that some classes of equipment will deteriorate with age even though given what may be considered ordinary or even high-grade care and maintenance. The presence of carbon and moisture in the insulation, and natural aging tend to weaken the insulation of many types of equipment, and this must be considered in arriving at a margin between the protectable level and the equipment strength.

4. Degree of Protection Justifiable and Sought

Finally and perhaps least definite of all, is the degree of protection which it is desired to obtain. Probably no system of insulation steps, even with protective devices, can be practically and economically applied which will preclude an occasional failure of some piece of equipment. In other words, 100 per cent protection is practically, and certainly economically, impossible. But there are differing degrees of near perfection, and different classes of service will each justify its separate different degree of near perfection. Therefore, it is quite apparent that in arriving at the protection margins to protect the basic levels, consideration must be given to what is a reasonable degree of protection to be expected and economically justified under a given set of conditions.

Determination of Protectable Levels by Use of Lightning Arresters

The determination of the margin between protectable levels and basic insulation levels obviously calls for a determination of the protectable level as well as the basic insulation level. If the protectable level is to be obtained by the use of a lightning arrester it is however, necessary to have a clear understanding of the basis of applying the arrester and of determining its performance. This has been done in the analysis which follows:

1. The protective characteristic of the lightning arrester is based on the arrester discharge at 5,000 amperes with the accepted 10–20-microsecond time characteristic. This value of 5,000 amperes is one which, as indicated by recent extended field tests,[3] may be encountered with sufficient frequency to justify its use.

2. The protective voltage levels of the arrester are taken as the maximum values (as distinguished from minimum or average values) for all arresters, whether distribution, line, or station type.

3. In applying arresters on a power system, it is desirable that the arrester maximum permissible rating should be not lower than the maximum power-frequency voltage to ground expected on the system under the most severe operating conditions.

Following this line of reasoning, the maximum rating of lightning arresters applied on an effectively grounded-neutral system has, for purposes of this analysis, been so chosen as to be not less than 1.3 times* the highest operating voltage (line to ground) to allow for the higher voltage which may exist under fault conditions. Where more severe conditions exist, it has been assumed that they will be considered as special cases.

4. In considering the entire group of normal system voltages, the numerical values have been increased on a fixed percentage basis to take care of the probable higher operating voltages to be expected on some systems throughout the country; and on account of system voltage regulation, the percentages of increase used are as follows:

For systems up to 8.3 kv rated voltage between phases, 20 per cent increase. For system voltages above 8.3 to 15 kv inclusive, 10 per cent increase; and above 15 kv, 6 per cent.

System voltages where hydro generation predominates are considered as requiring special consideration, although later discussion of obtainable insulation margins touches on this point.

5. In applying rod gaps as protection to the basic levels, a gap spacing equivalent to $3^1/_4$ times[6] the line-to-neutral voltage has been used. It is realized that this results in physical spacings so small in the lower voltage class of equipment that they may be considered impractical in this range.

In applying arresters to any power system, the one important criterion, that the 60-cycle voltage across the lightning arrester should not exceed its maximum rating, has been carefully observed. For arresters on an isolated-neutral system, it is assumed that so long as the arrester maximum rating is not below the power-frequency line-to-line voltage across the arrester at any time, the arrester itself is self-protected against power voltages. This reasoning is based on the large amount of experience throughout the industry in applying arresters on this basis. In applying arresters on an effectively grounded neutral system, on the other hand, recognition is given to the fact that the system line-to-ground voltage may, during fault conditions, considerably exceed normal. To allow for this the system line-to-ground voltage is increased 30 per cent, and this, as previously discussed, it is believed is sufficient to give the arrester dynamic-voltage protection in the preponderating percentage of cases, where system neutrals are effectively grounded. While it may be desirable in actual practice to add a small margin above this figure, the above basis has been used in this analysis.

* This is the figure that applies except in a very few special cases on our system. For fuller discussion of overvoltages see references 4 and 5.

Protection of Basic Insulation Levels—Margin Between Basic Insulation Levels and Protectable Levels

Table I has been prepared in an attempt to show what margins of protection to the basic insulation levels are possible by the use of protective devices on a sound engineering basis, in a range of system voltages normally encountered. It should be clearly pointed out, before discussing this table, that the analysis given herewith deals with the protection of the basic insulation levels themselves. The consideration of whether or not equipment is protected will, of course, depend on whether or not it conforms to the definite basic insulation level to which it has been assigned and the margin of protection existing above the protectable level. As will be brought out in the succeeding discussion, equipment conforming to any one of the basic insulation levels can in many cases be used in closely associated levels, and reasonable protection supplied unless the equipment itself cannot by virtue of its dynamic-voltage functional characteristics be so applied. (For example, a 2,300-volt transformer could not be used on a 15-kv system even if its basic insulation level could be adequately protected.)

Referring now to table I, in reference *a* is given the "insulation reference class" which conforms quite closely to the "preferred system voltage" now in common use. The second line (reference *b*) gives the highest normal system voltages which may be expected to be encountered on the distribution and transmission systems throughout the country. These have been selected on the basis of the operating voltages now in use by a great many of the larger utility companies.

To arrive at the 60-cycle basis for applying arresters to an ungrounded system, reference *c* has been developed by increasing the "highest normal system voltages" (reference *b*) by one of the three percentages of 20, 10, and 6 as mentioned above. By converting these to line-to-neutral values the voltages for the effectively grounded-neutral system have been obtained (reference *h*). In references *d* and *i*, the lightning arresters have been selected for both isolated and grounded-neutral systems using the maximum permissible rating for commercial arresters as now being made. The protective characteristics, that is, the maximum voltage permitted by the arrester at 5,000 amperes

discharge of these two groups of arresters (references *d* and *i*) are given in references *e* and *j*. Where double figures occur in any column, the first figure is for distribution or line-type arresters, and the second figure for station-type arresters. All these numerical values are the maximum for arresters of each class indicated, and conform to published data developed by and agreed upon by arrester manufacturers as representative of their product.*

Following the line of thought that a "safety factor" should be provided to take into account the large number of variables as enumerated above, the arrester *IR*-drop characteristic has been increased by a margin of ten per cent plus a flat value of 25 kv. These might be considered as the highest voltage levels that need to be considered in any study of basic insulation levels. Figures so arrived at for both isolated-neutral and grounded systems are given in references *r* and *s*.

In reference *q*, the proposed basic impulse insulation levels now being considered have been listed for the various insulation classes noted in columns 1 to 20 of the table. A comparison of the basic insulation levels in reference *q* with the highest lightning-arrester levels already referred to in references *r* and *s* shows that there is a reasonably close agreement between the basic insulation levels and the lightning-arrester characteristics plus margins (reference *r*) even for the isolated-neutral-system arrester, although it must be admitted that the line-type arrester for isolated-neutral service shows an almost consistent deficiency of margin between the basic insulation level and the highest voltage level to be expected from arrester performance figured on that basis. This is admittedly, however, a method of check that goes to some extremes in assumption of unfavorable protective conditions.

To determine the actual margin between the proposed basic insulation levels and the arrester *IR* drop at 5,000 amperes, references *f* and *k* have been developed for isolated and grounded-neutral systems respectively. Reference *f* shows the margins ranging from 19 kv in the low insulation class, with a general upward trend to 150 kv in the 345 class for station arresters. Line-type arresters do not show up so well however, although they do show a positive margin in their entire range of applicability. One point of distinct interest here is that shown in reference *k* which gives the margins of basic insulation levels over lightning arresters for grounded-neutral service. Here, the margin starts at 19 kv and increases to 480 kv in the 345 class. From the 2.5 class up, the margin between the basic insulation level and the lightning arrester ranges from equality to as high as 3 times as great for station arresters, and as high as 30 times as great in line arresters, for grounded-neutral systems when compared with the isolated-neutral system.

If higher margins than given in reference *f* are desired between basic insulation levels and lightning arresters for isolated-neutral service, this can be accomplished by using basic insulation levels in the next higher level. Margins obtainable in this way are shown in reference *g*. It will be noted that they are quite ample even with line-type arresters.

Again, where the system operates with an effectively grounded neutral, but abnormally high voltages may occur because of hydro generation, system extent, or other conditions, it is possible to use the proposed basic insulation level in the assigned insulation class and arrester in the next higher class, thus supplying the required margin of 60-cycle strength for the arrester and still offering a high degree of protection of the basic insulation level as shown in reference *l*. Many of these margins for the various insulation classes are of the same order of magnitude as is possible by applying standard arresters to isolated-neutral systems (comparison of references *f* and *l*). There is, of course, one notable exception in the 46 class; but for the 69 class and above, the protection thus afforded is equal to or better than that supplied on the isolated neutral system.

This same reference *l* shows the margins which are possible by using the appropriate arrester for grounded-neutral systems, and basic insulation levels in the next lower insulation class. For example, in the 138 class, it is shown that by using 115-class insulation on a 138-kv system with grounded-neutral arrester rated at 109 kv, there is a margin of 130 kv. This, of course, is less than the 230-kv margin obtained when using standard 138-kv insulation with the grounded-neutral arrester. However, it is more than the 90-kv margin obtained in using the standard 145-kv arrester on the isolated-neutral system.

The correlation of the proposed basic insulation levels with protective gap characteristics is given in references *m*, *n*, *o*, and *t*. It needs to be pointed out, however, that the gap data at low spacings in the range of insulation reference classes from 0.6 to 8.7, involving as they do gaps of one-inch spacing or less, are not presented as being particularly reliable or representative of gap spacings which any operating company would be willing to consider as practical in these voltage ranges.

The protective characteristics of a rod gap have been set up on a basis of using flashover data with a 1x5 negative impulse, and the average values of 50-50 flashover of such gaps have been increased 15 per cent to allow for tolerance of performance under practical conditions. This gives a figure which may be comparable to the *IR* drop characteristic of arresters at 5,000 amperes. This particular procedure in arriving at gap characteristics may be questioned, but it is presented here merely for comparative purposes to show the relative degree of protection which can be afforded by rod gaps using assumptions believed to be reasonable, and available data. It will be noted from reference *p* that margins of protection over the proposed basic insulation levels are positive up to the 69 reference class but become negative beyond this point. It should be remembered however, that these margins are based on a gap spacing corresponding to $3^1/_4$ times the maximum expected line-to-ground system voltage. It is entirely possible where experience with difficulties from line tripouts due to switching surges are favorable, or where the requirements of service continuity are not too stringent, to reduce the gap spacing and thus give positive margins, in some of the higher-voltage classes.

Practical Experience in Applying Lightning Protection

As previously reported[10] there was initiated some five years ago on the system of the American Gas and Electric Company a practice, applied to large power transformers, of locating directly on the transformer tank a lightning arrester correlated with the transformer strength. It is interesting to review the performance record since that time of transformers protected in this way, and compare the margins with those arrived at from the above analysis.

During the past four years there have been installed on the American Gas and Electric Company's 132-kv interconnected system nearly 700,000 kva of transformers which have been protected by lightning arresters mounted either directly on the transformer or as close as possible thereto. A review of the margins between the full-wave transformer test and the lightning-arrester *IR* drop at 5,000 amperes for the 132-kv windings of these transformers indicates values from approximately 40 kv to 205 kv. All of these 132-kv windings conform to the 115-kv

* By and large these values have been checked by laboratory test.

insulation class so far as voltage tests were concerned, some were delta connected and others built with graded insulation for grounded neutral service, with an appreciable saving in first cost.

With the use of standard transformer insulation on the 66-kv systems a margin of 30 kv was obtained between the strength of various transformers applied on them during this period and lightning arrester characteristic; in the 44-kv class, the margin was 33 to 96 kv; in the 34.5-kv class 37 to 80 kv; and in the 22-kv class 39 to 55 kv. It will be noted from the above figures that it has been possible to obtain with standard insulation on transformers as offered today, a substantial margin between the transformer full-wave test strength and *IR*-drop characteristics of lightning arresters of recent design. Further, in the higher-voltage class of 138 kv, it has been possible to utilize impulse insulation one class below the standard 138-kv class and still obtain margins which appear to be satisfactory. It should be pointed out in this connection, however, that in nearly all these cases of graded insulation using insulation in the next lower class, the lightning arrester has been mounted directly on or very close to the transformer.

On the 132-kv system, margins which we have been able to obtain in the past have not been quite as high as those indicated in table I or as obtained during the past four years. There are several reasons for this. One is that present-day arresters undoubtedly have better characteristics than those made several years ago thus permitting of larger margins, and another is that we have permitted ourselves to work on closer margins because we have generally impulse tested the very arrester which was used in service, while mounted directly on the transformer. Under such actually checked margins lower values are obviously still safe. It is further interesting to note that of some 750,000 kva of transformer capacity installed during the past four years involving circuits of 22, 33, 44, 66, 88, and 132 kv, not a single case of transformer failure has occurred where the transformer strength has been built up to the present insulation standards and protection supplied by modern lightning arresters with margins of the above indicated order.

Summary and Conclusions

1. The solution of the problem of rationalization of system insulation has advanced considerably since it was first proposed some 12 years ago, and the currently discussed series of basic insulation levels is a significant contribution toward its solution.

2. The proposed basic impulse insulation levels (reference *q* of table I) appear to provide a sufficient number of steps and their level values are suitably chosen so that modern arresters can be applied to protection of equipment built to these basic levels, and adequate margins realized under practically all conditions likely to be encountered in power-system operation.

3. The spacing of the basic-insulation-level steps has been so arranged as to make possible the securing of considerable flexibility in the choice in the margins of protection of equipment built to these levels without the assumption of burdensome economic handicaps.

4. While the margins between arrester characteristics or protectable levels and basic insulation levels appear adequate, considering the uncertain and unknown factors in lightning voltage surges which may be imposed on apparatus and the performance of a protective device under these conditions, caution is necessary. Particularly is this true if the arrester is expected to provide adequate protection to equipment located at some distance from the arrester as is required in some cases.

5. As a reasonable margin between the basic insulation level and lightning-arrester *IR*-drop characteristic, for general application, it is suggested that the arrester *IR* drop at 5,000 amperes increased by ten per cent and 25 kv should not be greater than the basic insulation level. This will influence in some cases the type of arrester chosen. Where the arrester is located at or close to the equipment to be protected, practical considerations may be permitted to allow acceptable margins below the value so arrived at.

6. With the acceptance of the proposed basic insulation levels (reference *q*, table I) the problem of assigning insulation strength to all classes of equipment in terms of these levels on an engineering and economic basis should not be difficult if a broad, industry-wide point of view is taken of the insulation rationalization problem.

7. Eventually it will be found necessary and desirable, in order to complete the solution of the problem of rationalization of system insulation, to provide definite margins in the levels of different equipment forming part of any given transmission system. It may be that this can best be done as part of the natural development which started with the work of investigation and determination of impulse characteristics of equipment, continued with the investigation of natural and system overvoltage phenomena, to be followed by the establishment of proper basic insulation levels and by the development of equipment to protect these levels and, finally, completed by the assignment of insulation strength to various equipment groups in terms of these levels. Whether such margins in levels for different equipment on one system should be established at the time the problem of assignment of insulation strength to various equipment groups in terms of basic insulation levels is carried through, or whether it will be best to await the experience gained by the assignment of practically co-ordinated levels for all the items of various equipment in a voltage class, is something that need not be determined at the present. The problem, in any case, is well enough in hand to permit patience with a view of not only allowing for integrating further experience, but also of making certain that no heavy burden is thrown on any portion of the industry concerned in this problem.

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Basic Impulse Insulation Levels

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Insulation Co-ordination

ONE of the early steps taken by the electrical industry, in an attempt to help solve the insulation-co-ordination problem was the formation of the National Electric Light Association (now Edison Electric Institute)-National Electrical Manufacturers Association Joint Committee on System Insulation Co-ordination in 1931. Before relating the work done by this committee, to acquaint the industry with what has been done to date and the present status of the work, it may be well to comment briefly, on what is meant by "insulation co-ordination."

It was generally recognized some ten years or so ago, as brought out by many papers in the technical press then and later, that the insulation strength of various classes of equipment was assigned not on the basis of the electric system as a whole, but rather on the requirements, as then understood, of each class by itself. This situation became strikingly evident in regard to the lightning, or impulse, strength of equipment which, until some 13 years ago, received comparatively slight consideration, largely because until then very little was known about the magnitude of lightning voltages on electric systems and the ability of insulation to withstand such voltages.

As information was obtained on both of these factors, it soon became apparent to some that it should be possible to arrange the impulse or lightning strength of equipment on any electrical system in a rational manner related to that particular system's requirements and so proportioned that electrical breakdown from lightning, if it did occur, could be confined to a predetermined location where the least damage would result to apparatus and service.

Closely associated with this idea, which basically required insulation steps or margins between the different classes of equipment, was the idea of setting up agreed-upon insulation levels. These levels, it has always been believed, quite logically should be based on the protection level afforded in the various voltage classes by available protective devices such as lightning arresters. This line of reasoning postulates then the setting up of levels which can receive a reliable degree of protection from the protective device, thus tending to minimize system service outages. But it goes further, and permits assignment to the different pieces of equipment of such strengths as should localize the failure, if such occurs, at that point in the electrical system where the least damage will result. In short, the term "insulation co-ordination" may be defined as the process of setting standards of insulation strength and assigning them to all the items of equipment in the various insulation classes in such a manner as to produce from an economic and operating standpoint both a maximum of protection and, if failure results, a minimum damage to the system.

Progress in Solving the "Insulation Co-ordination" Problem

The first step of the joint committee was the adoption in 1931 of a statement of principles which said:

"The co-ordination of insulation involves three steps:

"1. Establishment of insulation levels.

"2. Specification of insulation strengths of all classes of equipment in established insulation levels.

"3. Allocation of the insulation levels to the nominal system voltages, taking into account all operating and environmental conditions."

The establishment of levels on an impulse basis with definite kilovolt values given, was covered by a committee report[1] in 1937. The second step was undertaken in 1937 by the formation of the "Insulation Strength of Equipment Subcommittee of the EEI-NEMA Joint Committee on Co-ordination of Insulation" which has since been actively working on the problem. As a result of its work, it appears that the basic impulse insulation levels agreed upon in 1937 should now be reviewed in the light of our present knowledge, and the recent developments in the art. This is the subject of this paper.

Basis for Impulse Insulation Levels

In the 1937 report, basic impulse insulation levels were recommended which were the outcome of a study by a subcommittee of the insulation levels of existing substations and the performance obtained with those levels. The subcommittee did not select for the basic levels the best-insulated systems, but rather the average of a number of systems that were known to have a good operating record over the years. The values selected, therefore, were not unreasonably high but represented good general practice at the time of the survey.

In addition the then proposed values were checked against the performance characteristics of lightning arresters then available, and the flashover characteristics of rod gaps in use for commercial testing of transformers. This seemed to be a practical and sound basis on which to set up the levels.

Up to the time of the 1937 report, it had been customary to express impulse insulation strength in equivalent "inches of rod gap." The reason for this was that the testing technique of the various laboratories had not yet developed to the point where they could agree on the flashover value in volts of a rod gap. By 1937, however, this difficulty had been overcome and it was possible, therefore, to express the basic impulse insulation levels in volts. Considering the evolution of this step from rod gap and insulator testing, it was rather natural that the conversion from gap spacings to volts should be on a 50-50 flashover basis, that is, volts corresponding to gap spacings giving 50 per cent flashover and 50 per cent full wave when subjected to a standard impulse wave.

Since that time experience has been gathered in applying the values to actual practice. This has shown that the basis originally chosen requires clarification and adjustment.

It is not practicable to subject most types of apparatus to a series of flashover tests to demonstrate their insulation levels. Rather, a piece of apparatus is designed to withstand a certain impulse voltage when tested in parallel with a gap set for that particular voltage. It developed, then, that the impulse strength of apparatus was determined on one basis (withstand basis) and the required level was given on another basis (flashover basis). In order to reconcile these differences, it

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1. For numbered reference, see end of paper.

was necessary, therefore, to include a negative tolerance in the definition of basic insulation levels for demonstration of acceptability of equipment.

Since the basic impulse levels were proposed, manufacturers' testing laboratories have been working on refining impulse testing technique and the determination of the impulse strength of various apparatus. On the basis of this improved testing technique, it has been found quite recently that some of the porcelain insulators in bus and switch assemblies do not meet the basic impulse level proposed for the system voltage on which they are frequently used. As these comprise an important part of the system insulation, and as some insulators with seemingly inadequate insulation (as indicated by the suggested impulse levels) have given good performance in service, it is felt that further consideration should be given to that problem.

Definition of Basic Impulse Insulation Levels

The committee, therefore, set about redefining the 1937 basic insulation levels and put the values on a "withstand" rather than a "flashover" basis to eliminate the need for a tolerance factor.

To indicate how this redefining was accomplished, the old and new definitions are given below:

OLD DEFINITION

"Basic insulation levels are reference levels expressed in impulse crest voltage with a standard wave not longer than a 1.5x40-microsecond wave.

"Note: Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the 'basic insulation levels'. Due to the present limitation in testing, a tolerance of minus five per cent may be allowed when making full-wave tests on specified types of apparatus."

NEW DEFINITION

"Basic impulse insulation levels are reference levels expressed in impulse crest voltage with a standard wave not longer than 1.5x40-microsecond wave. Apparatus insulation as demonstrated by suitable tests shall be equal to or greater than the basic insulation level."

To clarify what is meant by "withstand basis," the definitions prepared by the laboratory subcommittee and amplified in a separate report are repeated.

WITHSTAND VOLTAGE (FOR AN IMPULSE)

"The withstand voltage of a test specimen under an impulse of any given wave shape, polarity, and amplitude, which does not cause disruptive discharge on the test specimen, is the crest value attained by that impulse."

Table I. Basic Impulse Insulation Levels

Reference Class (Kv)	Basic Level Based on Old Definition (Kv)	Basic Level Old Definition Reduced 5 Per Cent (Kv)	Proposed New Basic Level* (Kv)
1.2	32	30	30
2.5	53	50	45
5.0	63	60	60
8.66	80	76	75
			95
15	100	95	110
23	150	143	150
34.5	190	180	200
46	250	238	250
69	360	342	350
92	470	447	450
115	570	542	550
138	680	646	650
161	790	750	750
196	950	900	900
230	1,100	1,050	1,050
287	1,360	1,300	1,300
345	1,620	1,550	1,550

* These levels represent definite steps between which no intermediate values will be recognized. It should be noted that the levels are proposed and still under consideration of the joint committee.

NOTE: Attention is called to the fact that equipment carrying a power-frequency voltage rating which is numerically the same as the "Reference Class" in table I is not necessarily required to have the impulse levels given in the table.

CRITICAL WITHSTAND VOLTAGE (FOR AN IMPULSE)

"The critical withstand voltage of a test specimen under an impulse of any given wave shape and polarity is the crest value of that impulse when its amplitude is adjusted to be just below disruptive discharge on the test specimen."

RATED WITHSTAND VOLTAGE* (FOR AN IMPULSE)

"The rated withstand voltage of a test specimen is the crest value of an impulse of given wave shape and polarity, to be applied under specified conditions without disruptive discharge on the test specimen."

New Proposed Basic Impulse Insulation Levels

As a result of the foregoing considerations it is proposed to revise the 1937 levels as indicated in table I. The second column gives the 1937 levels which were on a 50-50 flashover basis. The third column gives the 1937 values reduced five per cent to put them on a "withstand" rather than a flashover basis. And the fourth column, which represents the new proposed levels, is practically the same as column three except that the figures have been rounded off to the nearest 5 kv, and further slightly altered in several cases to plot on a smooth curve against the "Reference Class." Also one new basic level of 110 kv has been added. In the first column the heading "Reference Class" has been used and values given to facilitate a comparison of the proposed levels with previously published[1] data.

* Note: When rated withstand test voltages are specified, it is customary to specify also a definite test procedure for demonstration purposes.

Considerable discussion has taken place as to the desirability of associating the impulse levels directly with operating voltages; and two radically different opinions exist on this point. One is, that since lightning voltages encountered in service are not dependent on the operating voltage, the impulse levels should not carry what purports to be an operating voltage rating; rather, arbitrary references such as A, B, C, etc., or 1, 2, 3, etc., might well be used for identification. The other point of view is that to omit the operating voltage designation will result in considerable confusion in the industry. It is outside the scope of this paper to discuss this phase of the problem here. Certain it is, however, that a co-ordinated system of insulation levels is desirable, and the values as given in the 1937 committee report have been extensively used in producing better insulation co-ordination on many electric transmission systems which exist today.

There are, however, still individual items of equipment that do not meet the 1937 basic levels, and in some cases, notably apparatus insulators and assemblies, some are low. The modification of designs covering these devices to meet the proposed levels cannot be undertaken without considering the economic burden on the electric industry. However, it may not be detrimental to the co-ordination program if they do not meet the proposed levels until further experience and discussion on this phase shows the desirability of making them conform to such levels.

Committee Representation

The formation of the joint committee on co-ordination of system insulation, started in 1931 through joint action of NELA (now EEI) and NEMA brought together for a study of the problem two vitally interested groups, one the users and system designers, and the other the manufacturers. Within the last few months the AIEE has agreed to join the above two groups in carrying on the work. As soon as the AIEE representatives are appointed the committee will function as a triple joint committee under the sponsorship of AIEE, EEI, and NEMA.

Summary and Conclusions

1. The adoption of basic impulse insulation levels by committee action in 1937 has actively stimulated the work of designing and

Recommendations for High-Voltage Testing

EEI-NEMA SUBCOMMITTEE REPORT

I—Introduction

(a). Scope of Committee Work

THIS subcommittee was established to study laboratory differences in results and methods in high-voltage testing and to propose laboratory technique to remedy these differences. Line-insulator, gap, and apparatus-insulator testing have been included in the scope of subcommittee activities. Some two years ago the subcommittee reported on flashover characteristics of rod gaps and insulators.[1] Since then continued work on high-voltage problems has resulted in a markedly improved understanding of the situation and some further recommendations have been agreed upon. Section II of this paper gives general recommendations for impulse testing and Section III outlines the scope of the Committee's recent activities and presents additional recommendations, particularly as to humidity corrections. All these activities are definitely related to the major problem of insulation co-ordination.

(b). Insulation Co-ordination

Insulation co-ordination is the correlation of the insulation strength of all the electrical equipment in a station or substation to meet a specified level or levels. In general, present practice is to have all the equipment meet a certain level of strength selected so that a protective device will control the path of discharge or flashover. Fundamentally, the purpose of impulse testing is to determine the relative performance of apparatus when subjected to surges such as those caused by natural lightning. In practice the co-ordination of apparatus insulation for impulse voltages is determined by tests which

(*a*). Demonstrate the insulation strength of the apparatus

(*b*). Demonstrate the protected voltage level established by the protective equipment

Uniform testing-equipment characteristics and testing methods and technique are, therefore, very desirable.

II—General Recommendations for Impulse Testing

The following practices related to impulse-voltage-testing equipment and methods have been found satisfactory and are recommended for immediate and general use, where standards for particular types of apparatus do not apply.

(a). Impulse Generator.

A composite schematic diagram of the discharge circuit of a surge generator is shown in figure 1. In many cases, however, some of the elements shown are omitted or are negligible.

A capacitance C_1 is charged by a rectifier to a voltage which produces discharge through a gap into a group of resistors. The impulse test voltage appears across resistance R_4, across which the test specimen is connected.

The capacitance C_1 may consist of several groups of capacitors which are charged in parallel and discharged in series by means of the Marx circuit. The inductance L_1, which is made as small as possible depends upon the physical design of the generator and the total length of the discharge circuit. The resistance R_1 consists of the inherent series resistance of the capacitors and connections and often additional lumped resistances. Additional inductance L_2 or resistance R_2 may be added at the generator terminal for wave-form control. R_3 is a resistor, for controlling the length of the wave, which may be used in addition to R_4 to obtain better regulation of the test voltage especially for short waves. Resistance R_4 may be used alone to control the length of the wave and it simultaneously serves as a voltage divider when a cathode-ray oscillograph is used for recording the wave shape. Capacitances C_2 and C_4 represent the electrostatic capacitances to ground of the high-voltage parts and leads. Included in C_4 are the capacitance of the test specimen and any additional load capacitance that may be required for correct wave shape. L_4 represents the inductance of the test piece. For some test specimens L_4 greatly influences the wave shape.

Because test pieces vary widely as to impulse characteristics and successful testing requires that certain recommended waves be obtained, adjustments of circuit constants are frequently required. Resistances R_2, R_3, and R_4, capacitance C_4, and inductance L_2 should be capable of adjustment.

For practical reasons one terminal of the impulse generator is solidly grounded during the discharge. Impulse voltage of either polarity is obtained by changing

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Personnel of EEI-NEMA subcommittee on correlation of laboratory data: J. E. Clem, chairman; A. C. Monteith, secretary; C. M. Foust, H. A. Frey, J. T. Lusignan, P. H. McAuley, K. B. McEachron, P. L. Bellaschi, and L. H. Hill.

1. Electrical Engineering (AIEE Transactions), June 1937.

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redesigning equipment to meet these levels.

2. Redefining the basic levels to require equipment to withstand the specified test (instead of permitting flashover at the specified values) requires a revision of the values adopted in 1937.

3. The proposed new basic levels appear to be based on sound fundamentals of the insulation co-ordination problem, and their early acceptance should result in a distinct forward step in carrying on the work to a conclusion.

4. It is generally understood that equipment carrying a power-frequency voltage rating which is numerically the same as the "Reference Class" in table I is not necessarily required to have the impulse levels given in the table. Setting up levels of a given value is one problem; assigning equipment to these levels is a separate and distinct one.

5. Discussion is invited by all those interested in this subject, particularly on those aspects of the problem dealing with the proposed new levels, designation of levels, and experience with the use of insulation conforming to or radically different from the levels adopted in the 1937 report.

Reference

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

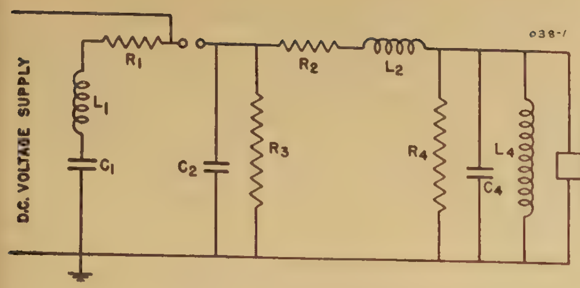

Figure 1. A composite diagram of the impulse generator discharge circuit

In practice R_2, R_3, L_2, C_4, and L_4 may be omitted or may be negligible compared to the other constants in a particular generator

the polarity of the charging circuit of the impulse generator.

(b). Impulse Waves

The most commonly used impulse wave is the 1.5x40-microsecond wave which is being considered for certain standards. The 1x5- and 1x10-microsecond waves have been used occasionally in the past. In the interests of simplification and uniformity, it is recommended that the 1.5x40 wave be universally adopted with proper tolerances for individual apparatus testing codes.

The International Electrotechnical Commission recognizes two waves respectively 1x5 and 1x50 microseconds. Also particular tests sometimes require specified wave fronts such as 50, 100, or 1,000 kv per microsecond.

In figure 2 is illustrated a typical impulse wave. For practical reasons a virtual zero-time point is established at O_1 and determined by a line drawn through the $0.1E$ and $0.9E$ points on the wave front. For the 1.5x40 wave O_1X_1 is 1.5 microseconds and O_1X_4 is 40 microseconds. Thus the standard 1.5x40 microsecond wave rises to crest voltage in 1.5 microseconds and decays to half crest value in 40 microseconds. In this way an impulse wave is specified as a T_1xT_2 wave where T_1 and T_2 are O_1X_1 and O_1X_4 respectively.

If the front is difficult to determine the virtual time-to-crest may be given as a constant such as 1.5 times the interval between the $0.1E$ and $0.9E$ points on the wave front. The proposed standard for transformers calls for 1.5 and, in this case, therefore, the virtual time-to-crest is $1.5X_2X_3$.

The actual recorded wave should conform to the specification. Spurious oscillations on the wave front should be damped out by a sufficient amount of resistance R_1 or R_2 to permit accurate measurement and analysis. The amplitude of such oscillations should not exceed five per cent of the fundamental wave.

Variations from the standard 1.5x40-microsecond wave shape should not exceed ± 0.5 microsecond on the wave front and $(+10, -0)$ microseconds on the wave tail. These figures refer to the test wave when no disruptive discharge occurs and where a particular apparatus standard involved does not specify a different tolerance. When the test piece characteristic is such that a wave within these limits cannot be obtained, the actual wave shape should be specified.

(c). Impulse Flashover

In testing an insulation specimen a range of voltage is usually found in which disruptive discharge may or may not take place, the percentage of voltage applications which cause disruptive discharge rising from zero at the lower edge of the range to 100 at the upper edge. When no disruptive discharge occurs a *full wave* is obtained. When a disruptive discharge occurs a *chopped wave* is obtained and this chopping may occur on the tail, at the crest, or on the front of the wave depending upon the voltage.

The *critical flashover voltage* of a test specimen under an impulse of a given wave shape and polarity is the crest value of that impulse when its amplitude is adjusted to cause flashover on 50 per cent of the applications.

(d). Volt-Time Curve

The volt-time curve is a graph of the crest values of flashover voltage against the time to flashover for a series of impulse applications between the full-wave test and front-of-wave flashover. The points should be chosen and distributed to fit the volt-time curve throughout this range. Ordinarily 20 to 40 points are desirable where air insulation is involved, but fewer points will give a good approximation of the curve and will suffice for the breakdown of expensive samples. The points for the volt-time curve are obtained from cathode-ray oscillograms of impulse discharges.

(e). Front of Wave Tests

Apparatus may be tested with flashovers occurring on the front of the wave. The rate of rise or steepness of the front may be varied by changing the circuit constants or the generator voltage or both.

The rate of rise is specified by the slope of the line through the $0.1E$ and $0.9E$ points on the front, figure 2, in kilovolts per microsecond and is called the effective rate of rise. The average rate of rise is often considered a more significant figure in front-of-wave tests. It has been defined as the slope obtained by dividing the crest voltage of the wave by the time to flashover measured from virtual time zero.

In some cases the lower part of the wave rises gradually to 30 or 40 per cent of the crest voltage and rises more rapidly thereafter. The $0.1E$ point does not give a true indication of the wave when used in determining rate of rise. The tangent for the more rapidly rising portion of the wave should be used in determining the rate of rise in this case.

It is recommended that, at least until it is possible to standardize more definitely on front-of-wave testing technique, both time-to-crest and time-to-flashover together with the method of specifying the rate of rise be recorded and reported in presenting data.

(f). Withstand Tests

To provide a suitable terminology and facilitate testing procedure for withstand tests, the following definitions are suggested.

Withstand Voltage (for an impulse). The withstand voltage of a test specimen under an impulse of any given wave shape, polarity, and amplitude, which does not cause disruptive discharge on the test specimen, is the crest value attained by that impulse.

Critical Withstand Voltage (for an impulse). The critical withstand voltage of a test specimen under an impulse of any given wave shape and polarity is the crest value of that impulse when its amplitude is adjusted to be just below disruptive discharge on the test specimen.

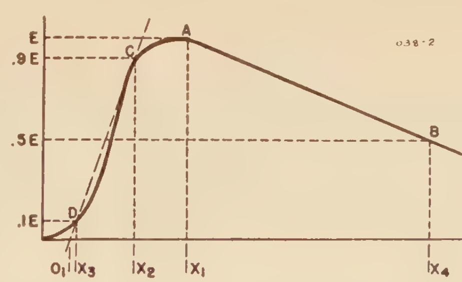

Figure 2. An impulse testing wave illustrating methods of designating significant characteristics of the wave

5. A 6-inch to 12-inch diameter measuring vessel

6. Precipitation measured in three places and a variation of from 0.24 to 0.16 inch per minute allowed throughout the string length

7. The voltage applied at a rate requiring at least ten seconds to flashover

The committee recommendations are being considered for a revision of the insulator test standard which is now in process of preparation by the AIEE.

(b). Flashover of Switch and Bus Insulators

Data submitted by several laboratories on outdoor switch and bus insulators have been assembled and are being prepared for submission to the joint committee.

(c). Critical (Minimum) Flashover Voltages for an Impulse

In response to requests from several sources, this committee took action on the use of the word "minimum" in the definition of this quantity as it now appears in ASA Definition Standards 35.90.125. The committee considered a great number of substitutes and finally reached agreement on the use of "critical flashover voltage for an impulse". This term is therefore recommended for immediate use and for substitution in the ASA definitions. The following definition is also recommended:

"The critical flashover voltage of a test specimen under an impulse of given wave shape and polarity is the crest value of that impulse when its amplitude is adjusted to cause flashover on 50 per cent of the applications."

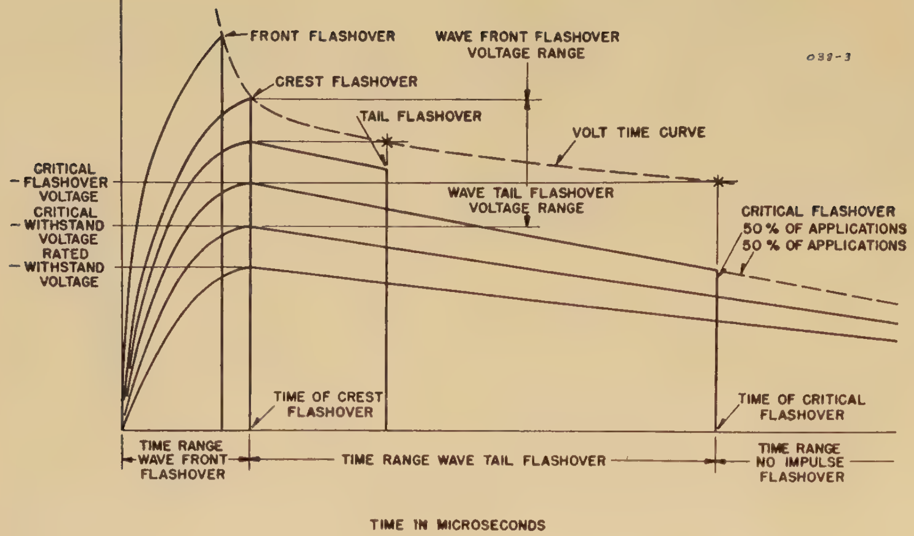

Figure 3. The series of impulse waves illustrates the terminology and definitions associated with impulse voltage testing

*Rated Withstand Voltage** (*for an impulse*). The rated withstand test voltage of a test specimen is the crest value of an impulse of given wave shape and polarity, to be applied under specified conditions without disruptive discharge on the test specimen.

These definitions are illustrated in figure 3.

(g). Deviations in Test Data

For positive-polarity critical withstand and critical flashover voltage measurements, the value obtained in an individual test in any laboratory should be within eight per cent of available standardized values, which are average values or levels obtained on similar apparatus from tests made in a number of laboratories. Negative-wave flashovers are inherently more erratic than positive-wave flashovers, with more chance of this deviation being exceeded. In front-of-wave and volt-time curve testing somewhat greater discrepancies may be expected. This eight per cent deviation was derived from intercomparison of laboratory results and is not to be considered as a tolerance in acceptance tests.

III—Progress Report and Additional Recommendations

(a). Wet Flashover Tests for Insulators and Bushings

This problem is concerned principally with present differences in recommended precipitations and water resistances, wherein the Insulator Standards No. 41 calls for 0.2 inch per minute and a water resistance of from 15,200 to 20,300 ohms per centimeter cube, and Oil Circuit Breaker Standards No. 19 calls for 0.1 inch per minute with a water resistivity of 12,000 ohms per centimeter cube.

The committee examined submitted data, sponsored tests in several laboratories, and studied the question in considerable detail deciding finally that a single standard of precipitation rate should be used and proposed 0.2 inch per minute. A resistance of 15,200 to 20,300 ohms per cm cube (6,000 to 8,000 ohms per inch cube) is also proposed. It was found easier to control the precipitation when the higher rate was used. As far as natural rain conditions are concerned, there appears to be no preference between 0.1 and 0.2 inch per minute. The range of 6,000 to 8,000 ohms per inch cube resistivity involves a correction on one type of apparatus from 0.98 to 1.02. The correction may be disregarded when tests are made within this range of resistivity. Tests may be made outside this range of resistivity provided recognized resistivity correction factors are available. In such cases the resistivity correction factors should be specified in the standards applying to each particular type of apparatus.

Attention was also given to details of wet test arrangements and the following recommended.

1. A 45-degree directional angle for the spray

2. A one-minute wetting before voltage application

3. A pressure range for the water of 35 to 60 pounds

4. All precipitation measurements taken with the test specimen in place

(d). Impulse Volt-Time Curves

In an effort to extend the co-ordination between laboratories on impulse tests obtained on rod gaps and insulators for the critical flashover voltage, volt-time curves from several laboratories on rod gaps, with the 1.5x40 wave, back to two microseconds have been compared. A wide disagreement which increased as the times became shorter was discovered. This disagreement reached ±20 per cent from the average of the laboratory curves for a single test at two microseconds. The disagreement has been shown to be partly caused by wave-shape differences particularly on the front. It has, therefore, been necessary to consider the basic problem of accurate control of impulse wave shapes. Additional tests and exchange of data are on schedule.

(e). Front of Wave Testing

This subject has been given attention by the committee and again differences

* Note: When rated withstand test voltages are specified definite test procedure for demonstration purposes should also be specified. In behalf of uniformity it is urged that where possible the procedure recommended in sections II and III of this paper be adopted.

between laboratories immediately involved consideration of means of production and accurate measurement of wave fronts. The problems here overlap those for item *d* above, "Impulse Volt-Time Curves," involving still more difficult problems of short-time testing.

(f). Impulse Withstand Tests

The committee was requested to consider methods of making withstand tests and accordingly has exchanged information pertaining to definitions, test methods, and values concerned. Active exchange of data is continuing and a test procedure is suggested for cases where other standards do not apply. The specific test should be covered in each apparatus standard but it is recommended that this suggested procedure be adopted where possible.

Specifications for Rated Withstand Impulse Tests

1. *Purpose of Rated Withstand Tests.* Withstand tests are made to determine that dielectrics will be capable of withstanding the rated withstand test voltage without a disruptive discharge on the test specimen.

(*a*). For insulator types on which disruptive discharge takes the form of a flashover in air, the rated withstand test voltage is given for standard atmospheric conditions and the test voltage to be applied shall be adjusted as outlined in paragraph 5.

(*b*). For insulator types in which disruptive discharge occurs only as a breakdown of the solid or liquid dielectric, atmospheric corrections are not applied.

2. *Specimen Mounting.* The specimen shall be mounted for test in accordance with the requirements of the apparatus code applying to the specimen (for example, for bus insulators NEMA Publication 35-28 for 60-cycle flashover tests or new AIEE Standards No. 41 when accepted).

3. *Impulse Wave Shape and Polarity.* The wave shape, tolerances, and polarity shall be as specified by the apparatus code applying to the specimen. In general, the polarity shall be that which produces the lower critical withstand voltage on the specimen.

4. *Voltage Measurement.* The amplitude of the applied impulse waves shall be measured by the methods approved in the latest revision of AIEE Standards No. 4.

5. *Correction for Atmospheric Conditions.* For the conditions indicated in 1*a*, the rated withstand voltage shall be corrected with air density and humidity correction factors applicable to the test specimen such that:

$$V = RWV \times \frac{D}{H}$$

where

V = amplitude in kilovolts of the test wave
RWV = rated withstand voltage
D = relative air density
H = humidity correction factor applying to the test specimen

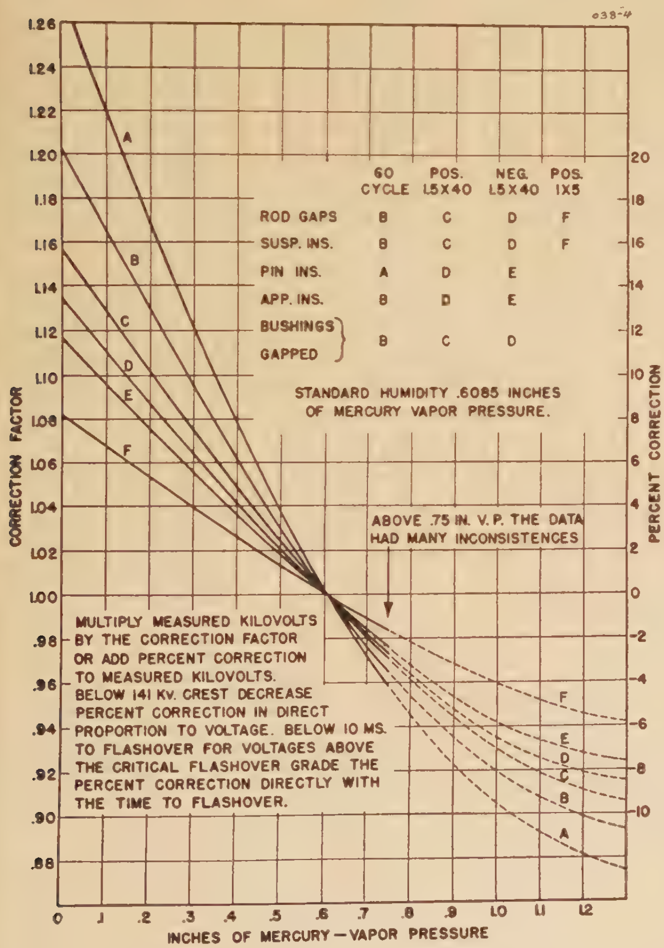

Figure 4. Humidity correction factors for flashover voltages of gaps, insulators, and bushings, based on average data from several laboratories

6. *Method of Test.* Three consecutive impulses shall be applied to the test specimen. The crest voltage of each shall not be less than the rated withstand voltage properly corrected (sections 1 and 5). If a disruptive discharge does not occur, the specimen shall be considered as having met the test.

If two or three of the applied impulse waves cause disruptive discharge, the test specimen shall be considered as having failed the test. If one of the applied impulses cause disruptive discharge,* three additional impulses shall be applied. If disruptive discharge does not occur, the specimen shall be considered as having met the test.

(g). Sphere Gap and Cathode-Ray Oscillograph Measurement Comparisons

Several laboratories have submitted comparative data on sphere-gap and cathode-ray-oscillograph measurements of crest voltages based on the criterion for measurement accuracy recommended in AIEE Standards No. 4 (revision of December 1937). Agreement is well within the five per cent stipulated in all cases and there appears to be no tendency for either method to give consistently higher values than the other.

(h). International Electrotechnical Commission Publication No. 60; General Specifications for Impulse Voltage Testing

Committee consideration has been given to this standard with the point in view of judging the value of such a general standard for equipment not now covered in particular apparatus or materials recommendations or codes. In the United States the trend to date has been to include all impulse testing recommendations in three places as follows:

1. All definitions of terms in the American Standards Association definitions.

2. All recommendations on measurements in AIEE Standards No. 4, Measurement of Test Voltage in Dielectric Tests.

3. All recommendations as to waves to be applied and circumstances peculiar to their application to be included in the particular apparatus or material codes.

This trend has been a healthy one and, rather than develop a new general standard, it is suggested that section II of this paper be used as an appendix to existing standards.

(i). Correction Factors

Attention has been given wherever flashover results were being considered, to necessary corrections for relative air density and humidity. In the previous

* For solid dielectrics disruptive discharge results in permanent damage and the ruptured dielectric must be replaced.

Table I

Time to Flashover	Measured Kilovolts	Relative Air Density, Divide by	Humidity, Multiply by	Corrected Kilovolts
5	108	0.95	1.077	122
4	108	0.95	1.077	122
3	113	0.95	1.023	122
2	126	0.95	1.015	135
1	158	0.95	1.007	168
0.5	208	0.95	1.004	220

report of the committee humidity correction factors for 60-cycle and positive-wave impulse flashover of rod gap and suspension line insulators were submittted. Since then this work has been extended.

The dielectric strength of air is affected by its temperature and pressure. Also flashover voltages for nonhomogeneous electric fields vary with the absolute humidity of the air. Consequently, the following standard air conditions have been adopted:

Temperature	25 deg C (77 deg F)
Barometric pressure	760 mm (29.92 in.)
Humidity (vapor pressure)	15.45 mm (0.6085 in.)

Correction factors have been established and flashover voltages should be referred to standard air conditions. Similarly, in withstand tests, where air insulation is involved, corrections must be made for the air conditions at the time of the test. Where tests are made at high altitudes the barometric pressure correction automatically compensates for altitude.

1. *Relative Air Density.* The temperature and pressure are combined into one unit called relative air density, which is unity at 25 degrees centigrade and 760 millimeters pressure. The relative air density for any other condition is given by the formula

$$\text{r.a.d.} = \frac{0.392B}{273+T}$$

where

B is barometric reading in millimeters
T is temperature in degrees centigrade

The flashover voltage of disruptive discharges through air is corrected by using the same correction irrespective of frequency of the voltage causing flashover.

2. *Humidity.* The humidity correction varies for different types of apparatus and for different forms and polarities of test voltage. Corrections for a number of different conditions have been evaluated by actual tests over a wide range of absolute humidity and are given in figure 4. The corrections are given both as a correction factor (multiplier) and as a per cent correction (to be added). The latter is used in revising the amount of correction applied at low voltages and at short times. If, for a particular test, none of the standard correction curves applies, the one which most nearly approximates the conditions of wave form, polarity, and type of apparatus should be used.

Correction Procedure

(*a*). *Full Wave Test and Critical Flashover Voltages.* The measured test voltage is divided by the relative air density and multiplied by the humidity correction factor to give the equivalent voltage for standard air conditions. If the measured voltage is less than 141 kilovolts crest, the humidity per cent correction should be decreased in proportion for insulators and rod gaps.

$$H^1 = H\frac{\text{kv}}{141}$$

where H is the per cent correction from figure 4. The humidity correction factor is then $\dfrac{100+H^1}{100}$.

(*b*). *Front-of-Wave Tests and Volt-Time Curve Voltages.* In correcting volt-time curves to standard air conditions the following standard procedure should be followed:

1. Use the full relative air-density correction at all points on the volt-time curve. In practice, divide voltage values by the relative air density, which corrects to standard temperature and barometric pressure.

2. Use the humidity correction factors for different waves and apparatus, as given in figure 4.

(*a*). When the critical flashover voltage is less than 141 kv crest, grade the per cent correction directly with the voltage.

(*b*). For times to flashover less than ten microseconds, when the corresponding voltage value exceeds the critical flashover voltage, grade the per cent correction directly with the time to flashover.

In practice, multiply the critical flashover voltage values and all voltage values for times greater than ten microseconds by the humidity correction factor. For voltages exceeding the critical flashover voltage at times less than ten microseconds multiply the humidity per cent correction by a factor equal to the corresponding time to flashover divided by ten. The humidity correction factor used as a multiplier for short times then becomes 100, plus this reduced per cent correction divided by 100. When the transition point is considerably less than ten microseconds, judgment is necessary to maintain a smooth curve. When the critical flashover voltage is less than 141 kv crest, decrease the per cent correction in direct proportion to the voltage.

Example

Assume the following volt-time curve for a 1.5x40 positive wave obtained on a rod gap at relative air density 0.95 and at a vapor pressure of 0.2 inch.

Time to Flashover (Microseconds)	Kilovolts
5	108
4	108
3	113
2	126
1	158
0.5	208

For a rod gap at 0.2 inch humidity, the correction factor is 1.101 or the per cent correction is 10.1 from figure 4.

(*a*). Correct for a voltage below 141 kv. For a critical flashover voltage of 108 the per cent correction becomes $108\times10.1/141=7.7$

(*b*). Correct for the time to flashover. At two microseconds the per cent correction is $2\times7.7/10=1.54$ or the correction factor is 1.0154. Similarly for times less than four microseconds in this case. The corrections for the curve are then as shown in table I.

The corrected kilovolts give the volt-time curve for standard air conditions.

All corrections given are subject to revision from time to time, as more exact test data become available.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Transactions

Preprint of Technical Papers Comprising Pages 603–642 of the 1940 Volume

Transient Starting Torques in Induction Motors

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Synopsis: A transient fundamental-frequency torque is shown to occur in the starting of all induction motors. For full-voltage starting on a general-purpose squirrel-cage motor, this torque may be as high as two or three times the pull-out torque. A consideration of such torques is particularly advisable for cases where induction motors are started and stopped frequently or continuously, since under such conditions mechanical failure of the motor or associated parts, gearing, couplings, etc., may occur if the stresses exceed the endurance limit of the material.

A method of analysis is given for calculating the transient electrical torques acting in the case of a locked rotor; the results obtained by means of this analysis are compared with test data obtained on a special locked-rotor test setup. A method is also given for calculating shaft torque from the electrical torque in the usual application. Test results also indicate that this method is satisfactory for practical use.

FOR many years engineers have used the average starting torque and pull-out torques of induction motors as the basis for mechanical design of shafts and couplings, not always realizing that high alternating torques existed at the moment of starting. So far as the authors are aware no one has published any practical analysis, or even a discussion of this problem.

The analysis and tests given in this paper show that when a motor is thrown on the line by the sudden closing of a switch, the contacts of which close simultaneously, a fundamental-frequency electrical torque which may be several times the pull-out torque, will be developed for the first few cycles. If the closing of the switch contacts of the several phases is not simultaneous, this alternating torque may be higher, and in the worst case of 90 electrical degrees lag, about 40 per cent higher alternating torques will exist.

The actual shaft and coupling torque will depend on the flexibility of the shaft and coupling and the inertia of the load and the motor. It is apparent that if the natural frequency of the mechanical system consisting of rotor, coupling, and load happens to be quite near the current supply frequency, the peak shaft torques may even exceed the electrical torque due to the resonance effect, particularly for high load inertias. Also, if the coupling has backlash or a nonlinear torque-angle characteristic, an increase in torque may be had due to impact effects. Where the driven-load inertia is of the same order of magnitude or smaller than the motor inertia, a reduction in shaft torque is to be expected.

The fact that trouble from this source has been encountered only in exceptional instances may probably be explained as follows: (1) Usually the torsional natural frequency of the system is well below the current supply frequency so that most of the alternating torque is absorbed by the inertia of the rotor and is not transmitted to the shaft; (2) in most applications, starts and stops are relatively few so that a fatigue condition due to repeated loadings does not exist. Consequently, for such conditions, transient torques several times the endurance limit for indefinitely repeated loading may be absorbed without harm. Another way of explaining this is that the endurance curve for the shaft material (with stress concentration present) rises steeply as the number of cycles of repeated stress is reduced; (3) ample safety factors in shaft design based on experience are normally used; and (4) in most applications, the driven-load inertia is of the same order of magnitude or smaller than the motor inertia.

The mathematical analysis is carried out for the case of the locked rotor and yields the maximum torque which will be obtained at full voltage. For the case of reduced-voltage starting with an autotransformer or star-delta connection some flux may remain in the motor at the instant full voltage is applied with the result that even higher torques may occur. These latter conditions are, however, not considered in the present paper.

Electrical Torques

Before attempting a mathematical analysis of the problem, it is desirable to develop a physical picture of what is going on inside the machine under these transient conditions. It is simpler to think in terms of a two-phase machine, since the two windings are in space quadrature and have no mutual inductance. It will be shown in the appendix that the three-phase currents of a three-phase machine can be resolved into components acting on two quadrature axes (α and β).

In dealing with the transient torques in a machine, probably the most useful form of analysis is based on the difference in the products of fundamental current on each axis and fundamental air-gap flux on the axis in quadrature. In per unit notation[1]

$$T = i_{1\alpha}B_\beta - i_{1\beta}B_\alpha$$

or if the magnetizing current i_m on each axis is expressed in per-unit notation, *the unit value being the current required to produce a flux sufficient to induce rated voltage at no load*, then:

$$T = i_{1\alpha}i_{m\beta} - i_{1\beta}i_{m\alpha} \tag{1}$$

The sudden application of an alternating voltage to a reactive circuit will produce a transient asymmetrical flux and current depending on the point on the voltage wave at which the switch is closed.

The fundamental-frequency transient torque results from the reaction of the asymmetrical flux on one axis with the

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The authors wish to express their appreciation to E. C. Whitney for his assistance in carrying out the analysis for electrical torques developed in this paper.

1. For all numbered references, see list at end of paper.

alternating current on the other, and also to the reaction of the asymmetrical current on one axis acting on the alternating flux in the other. The asymmetrical flux and the associated fundamental torque decay slowly, since these depend on the magnetizing inductance. The asymmetrical current and its associated fundamental torque decay rapidly since these depend on the leakage inductances. The torque components due to asymmetrical current and to asymmetrical flux are initially equal and of opposite sign.

The mathematical analysis is given in appendix B for the case of a locked rotor. The actual case of the machine coming up to speed becomes much more involved. However, the peak of this alternating shaft torque (except where exact resonance is approached) comes within the first few cycles and in this time the rotor will not have attained more than a few per cent speed and the effects of rotation on the transient currents and flux are negligible.

The results of this analysis of transient locked rotor torques are given in equation 11 in terms of the starting torque and locked power factor, for the case of simultaneous application of voltage to all phases.

For small machines, or larger high-torque machines, where the locked power factor ($\cos \phi$) is not less than 0.3, the component of alternating torque due to the asymmetrical current dies out so rapidly as to be negligible and the peak electrical torque may be obtained by neglecting the terms involving λ_2, which gives:

$$T_{1m}=T_s\left(1+\frac{1}{\cos \phi}\right) \qquad (2)$$

For a large motor with low locked power factor the component due to the asymmetrical current decays more slowly. The resultant alternating torque starts at zero and builds up to a maximum in a few cycles, and the peak electrical torque will still be approximately that given by equation 2.

These equations apply only when there is simultaneous voltage application on all three phases. Such a condition is often difficult to obtain with actual switches or contactors. For this reason a second analysis was carried out by assuming that the switch was closed on one phase of the equivalent two-phase machine 90 electrical degrees (or 0.004 second at 60 cycles) later than on the other phase. On the three-phase machine this would mean that the third phase was closed 90 electrical degrees after the closure of the second phase. The results of this analysis are given in equation 12. Again neglecting terms involving λ_2 the peak electrical torque becomes:

$$T_{2m}=T_s\left(1+\frac{\sqrt{2}}{\cos \phi}\right) \qquad (3)$$

Values of peak torque found for such conditions are around 20 to 40 per cent higher than those obtained on the assumption of simultaneous voltage application.

A physical explanation of the increased torque due to closing the last phase 90 degrees later may be had, by considering that this may result in maximum asymmetrical flux in each of the two axes which gives a resultant asymmetrical flux $\sqrt{2}$ times the maximum value on one axis.

Tests to Determine Electrical Torques

In order to check up on the theoretical work, a special locked-rotor test arrangement (figure 1) so designed as to record transient torques was used. Essentially, it consists of an arm attached to the motor shaft and held at its end by a thin tool-steel bar. Under the action of pulsating torques, this tool-steel bar is stretched or contracted, these transient movements being recorded on an oscillograph by means of a magnetic strain gauge.[2] By using a tool-steel bar, a fairly high natural frequency, relative to the current supply frequency, was obtained. The relation between rotor torque and oscillograph-beam deflection is established by a static calibration.

In figure 2 a typical curve of transient starting torque obtained on a high-resistance induction motor is shown by the full lines. It may be seen that this consists essentially of a pulsating component at the current supply frequency which dies out after a time. For comparison, a calculated curve obtained from equation 11 is also shown.

A summary of ratios of maximum torque T_m to nominal starting torque T_s obtained on various rotors at different frequencies (so that $\cos \phi$ varied from about 0.6 to 0.95) is shown in figure 3. It may be seen that while there is considerable scatter in the results, most of the test points occur between the limits of the curves defined by the approximate equations 2 and 3, with the latter equation yielding an approximation to the upper limit.

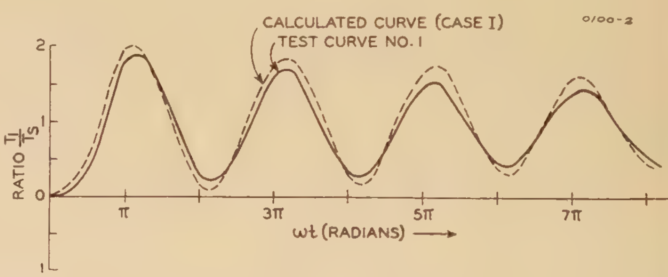

Figure 2. Comparison of test and calculated torque curves for typical high-torque induction motor

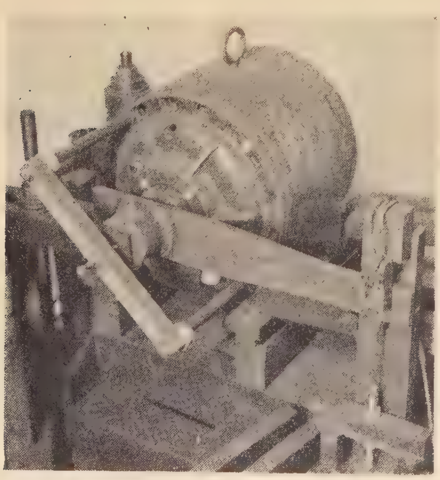

Figure 1. Test setup for measuring electrical torques

Transient Shaft Torques

General Method—Linear Couplings

The preceding discussion has been primarily concerned with the transient electrical torques acting on the rotor at the instant of starting. In most cases, however, the designer is mainly concerned with the transient shaft torques, since on these depends the design of the mechanical parts. As mentioned before, these shaft torques depend not only on the electrical torque, but also on the other characteristics of the drive including rotor and load inertias, flexibility of shaft-coupling system, and in certain cases, the shape of the torque-angle characteristic of the coupling.

In many cases of practical interest, an induction motor is coupled to a heavy inertia load by means of a flexible coupling. An example of such construction is the roll-table drive used in continuous strip mills. In such cases the system

may usually be represented for purposes of analysis by a single degree-of-freedom system consisting of a mass, representing the motor, connected by a spring, representing the coupling and shaft flexibility, to a rigid body. This analysis will hold approximately where the equivalent driven-load inertia is large compared to that of the motor. As will be shown later, the results for this case may also be used when the load inertia is finite.

If we neglect damping, the known differential equation of motion for such a system, assuming a coupling with a linear torque-angle characteristic is

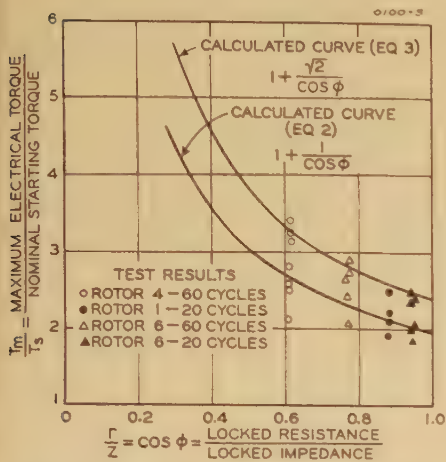

Figure 3. Comparison of test and calculated values of ratios between peak electrical torque and starting torque

$$I_m\frac{d^2\theta}{dt^2}+k\theta=F(t) \tag{4}$$

The shaft torque may be determined by introducing $F(t)$ as given by equations 11 or 12 into equation 4 and integrating, the integration constants being determined from the initial conditions which require that when $t=0$, $\theta=0$, and $d\theta/dt=0$. Because of the rather complicated expression for $F(t)$, such an integration becomes very laborious and for this reason the following alternative method was used.

By using the principle of superposition, it may be shown that if damping is neglected, the angular displacement for the single degree of freedom system under consideration is given by:[3]

$$\theta=\frac{1}{\omega_n}\int^{t_1}\frac{F(t)}{I_m}\sin\,\omega_n(t_1-t)dt \tag{5}$$

Application to High-Resistance Rotors

Unless the damping is unusually high, it is justifiable where high-resistance rotors are involved to neglect damping in practical systems where the natural frequency of the system is much less than the current supply frequency since in such cases the peak torque will occur within the first cycle of oscillation at the natural frequency.*

Assuming as before that the magnetizing reactance is very large compared to the rotor or stator resistance, the decrement factor λ_1, will be small compared to ω. Hence, the term $\epsilon^{-\lambda_1 t}$ may be taken as unity in the expression for $F(t)$, since during the first few cycles of applied voltage during which the maximum shaft torque occurs, this term will differ but little from unity. With this simplification, by integrating equation 5 the expression for shaft torque takes the form:

$$T=T_s\{1+\beta_1\epsilon^{-\lambda_2 t}+\beta_2\epsilon^{-\lambda_2 t}\sin\,(\omega t+\gamma_2)+\beta_3\times\sin\,(\omega_n t+\gamma_3)+\beta_4\sin\,(\omega t+\gamma_4)\} \tag{6}$$

where β_1, β_2, β_3, β_4, γ_2, γ_3, γ_4, depend on ω/ω_n and ϕ.

For typical high-resistance rotors ($\cos\phi>0.3$), it may be assumed that the term $\epsilon^{-\lambda_2 t}$ dies out very rapidly during the first cycle of applied voltage, so that it may be neglected as far as any contribution to the peak torque is concerned. (The results, however, should not be applied when low-resistance rotors are being considered.) In addition, in practical cases where ω_n is not over say $\omega/2$, it may be assumed as a first approximation, that the phase angles γ_3 and γ_4 are such that the torque components β_3 and β_4 add directly. (This will yield results somewhat on the safe side, the closeness of the approximation being greater for smaller ratios of ω_n/ω.) With these simplifications, the peak shaft torque (for high-resistance rotors) becomes:

$$T_m=T_s\{1+\beta_3+\beta_4\} \tag{7}$$

Values of the ratio T_m/T_s obtained by using this method for various values of $\cos\phi$ are plotted in figure 4 for simultaneous voltage application on both axes and in figure 5 for voltage application on the β axis 90 degrees later than on the α axis. It may be seen that the latter assumption yields definitely higher shaft torques. It should also be noted that peak transient shaft torques as high as four to five times the nominal starting torque may occur for cases where $\cos\phi=0.5$ and $\omega_n/\omega=0.5$. In utilizing these curves, it should be borne in mind that because of the assumptions made, the ratios T_m/T_s may be somewhat overestimated for the larger ratios of ω_n/ω.

* When operating with a natural frequency not far from the supply frequency, damping should be considered for an accurate solution.

An alternative method for obtaining an approximate solution is to take $\epsilon^{-\lambda_2 t}=0$ and $\epsilon^{-\lambda_1 t}=1$, as before, in the

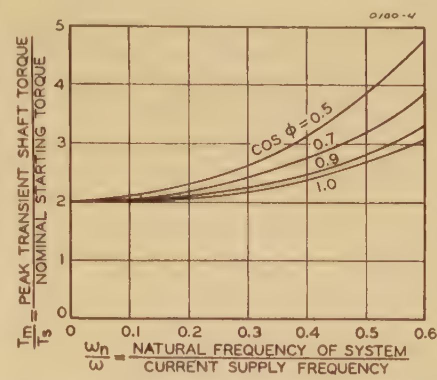

Figure 4. Variation of maximum shaft torque with torsional natural frequency—simultaneous voltage application

Infinite load inertia and simultaneous voltage application in all phases assumed

expressions for torque given by equation 11 or 12. These approximate expressions are then substituted for $F(t)$ in the differential equation (4) and the integration carried out. Assuming as before that the torque components at the natural frequency and at the current supply frequency add directly, peak torques somewhat lower than those given by the curves of figures 4 and 5 are obtained.

The previous discussion deals only with the case where the equivalent load inertia is infinite compared to that of the motor rotor. Where this is not the case, that is, if the load inertia is of the same order of magnitude as the motor inertia (a condition which frequently occurs in practice), a comparison of the differential equations for the two cases shows that the curves of figures 4 and 5 may still be used provided that the natural frequency is determined by using an equivalent moment of inertia

$$I_e=\frac{I_mI_r}{I_m+I_r}$$

instead of I_m, and provided that the peak torque, thus found, is reduced in the ratio $I_r/(I_m+I_r)$.

Where the torque-angle characteristic of the coupling is nonlinear (as it is in many practical couplings) the differential equation (equation 4) will still apply if the constant k is replaced by a function $f(\theta)$ which represents the torque-angle characteristic of the coupling. Usually an analytical solution of this

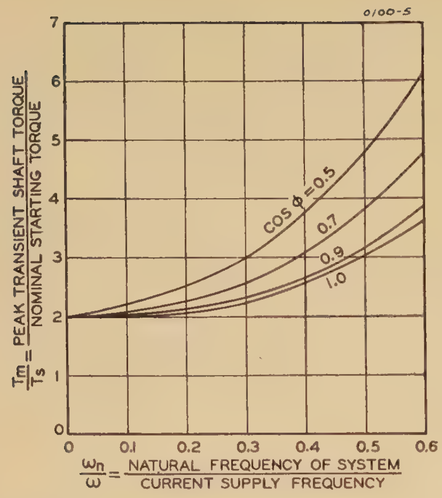

Figure 5. Variation of maximum shaft torque with torsional natural frequency—nonsimultaneous voltage application

Infinite load inertia and voltage application β axis 90 electrical degrees later than on α axis

modified equation is impractical and in such cases a numerical solution* has given good results when compared with actual test values.

The peak shaft torques obtained by using the methods of calculation outlined herein have been compared with the results of actual torque measurements on a typical high-resistance induction motor coupled to a heavy inertia load by means of a flexible coupling. The torques were measured by means of a magnetic strain gauge so mounted as to measure shaft twist, the results being recorded on an oscillograph. The tests were carried out by using a number of different makes of flexible couplings. Although a complete discussion of these results is beyond the scope of the present paper, it may be mentioned that the results indicate that the methods of calculation developed herein for high-resistance rotors are satisfactory for practical application.

Low-Resistance Rotors

For low-resistance rotors the $\epsilon^{-\lambda_2 t}$ term in equations 11 or 12 of appendix *B* cannot be neglected. In the first instant, $\epsilon^{-\lambda_2 t}$ is unity and the two components of alternating torque are found to cancel out. After a few cycles $\epsilon^{-\lambda_2 t}$ has decreased considerably and the alternating electrical torque approaches the value obtained from equations 11 and 12 by putting $\lambda_2=0$. Because the alternating torque builds up slowly an approximation to the peak torque should be had by adding directly (1) the shaft torque component at the natural frequency (produced by the impact effect of the average electrical torque applied in the first instant after starting) and (2) the torque component at fundamental frequency due to the alternating electrical torque. Where the load inertia is large, the first of these components will be about twice the average electrical torque in the first instant after starting. Where the ratio ω_n/ω is not low, it would appear that a rough estimate of this average torque could be obtained from equations 11 and 12 by taking $\epsilon^{-\lambda_2 t}$ as unity and neglecting the trigonometric terms. This gives an average electrical torque of $2T_s$ and $(1+\pi/2)T_s$ for the simultaneous and nonsimultaneous cases respectively, with resulting peak shaft torques of $4T_s$ and $(2+\pi)T_s$ due to the impact effect for the two cases. It should be noted that these values may be somewhat too high for the lower values of ω_n/ω and for very low values (say 0.1 or less) the peak impact torque may be taken as $2T_s$. To this must be added the fundamental-frequency shaft torque component due to the alternating electrical torque which is $\pm 1/(\omega^2/\omega_n^2-1)$ cos ϕ or $\pm\sqrt{2}/(\omega^2/\div\omega_n^2-1)\cos\phi$ for the simultaneous and nonsimultaneous cases, respectively, the negative sign being used if $\omega<\omega_n$. For a more accurate solution in any particular case equations 11 or 12 may be taken as the expressions for $F(t)$ in equation 5 and the integration carried out. The fact that mechanical damping is neglected when figuring the torques by these methods means that the calculated values of shaft torque may be somewhat too high particularly where the natural frequency is not far from the current supply frequency. Where the load inertia is not large compared to the motor inertia, these values should also be reduced in the ratio $I_r/(I_m+I_r)$ as discussed previously.

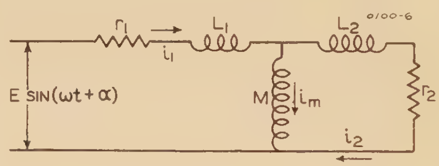

Figure 6. Equivalent circuit used in analysis

Conclusions

1. All induction motors started by sudden application of voltage will have transient fundamental-frequency electrical torques. If started at full voltage the peak electrical torque may be two times the pull-out torque or more.

2. The transient electrical torques can be calculated by equations 11 and 12. For a high-torque motor the peak electrical torque is given approximately by equations 3 and 4.

3. The test results (figure 3) show that the method of analysis is sufficiently accurate.

4. Mechanical torques for the common case where the torsional natural frequency of the mechanical system is well below the supply frequency are given by curves of figures 4 and 5 for high-torque motors. A method is also outlined for motors with low locked power factor.

Appendix A

The Equivalent Two-Phase Machine

Park[4] has shown how the currents of a three-phase machine may be resolved into direct- and quadrature-axis components on the two axes of the rotor. More recently Stanley[5] has given a somewhat more general analysis by resolving the three-phase currents along any two quadrature axes. Examination of the resulting equations of this method shows that they are exactly the same as for a simple two-phase machine, except for zero-sequence currents (that is, current flowing in the neutral).

One can arrive at this same conclusion by simple physical reasoning. The current in one phase may be thought of as dividing between the other two phases and this will be taken as one of the two-phase components. The second two-phase component will be the difference in the currents of the other two phases. So long as there are no neutral currents, the resultants of these two-phase components will be equal to the real three-phase current in any phase.

In order to establish the relation between the equivalent two-phase components, take I and E as the line currents and phase-to-neutral voltage of the three-phase machine. Then I and $3/2E$ are the current and voltage of the first phase of the equivalent two-phase machine, and $\sqrt{3}/2$ and $\sqrt{3}E$ are the current and voltage of the second phase. Either of these two phases could be used as the reference, but it is more convenient to use the first. For this case the equivalent two-phase current is the same as the three-phase current, but the two-phase voltage and the inductance and resistance values will be taken as 3/2 times the three-phase line-to-neutral values.

The locked two-phase machine consists essentially of two independent transformers and the usual transformer equivalent circuit (figure 6) can be used accurately to represent current and voltage relations on each axis. The inductance coefficients L_1 and L_2 are the leakage inductances of the primary and secondary, and are numerically equal to the ohms reactance divided by $2\pi f$. M is the magnetizing inductance.

The secondary constants L_2 and r_2 are converted to the primary as is customary in all induction-motor calculations. Actually the secondary reactance and resistance are in most cases affected by eddy currents. The locked values of these constants will be used because they are correct for the fundamental-frequency currents, and the error is only in the decrement.

* See Timoshenko, reference 3, page 126, for an example of such a solution applied to a similar case.

Appendix B

Calculation of Transient Electrical Torques

In line with the discussion of appendix *A* the induction-motor winding is assumed divided into α and β components with axes at 90 degrees. Each component is represented by the equivalent circuit of figure 6. The voltage applied to the circuit is given in the general form $E \sin(\omega t+\alpha)$ and the parameter α may be so chosen for each axis that the voltages acting on the α and β axes will be 90 degrees apart. Referring to figure 6, assuming constant values of L_1, L_2, and M, the following differential equations hold:

$$(r_1+pL_1)i_1+pMi_m=E\sin(\omega t+\alpha)$$

$$(r_1+pL_1)i_1+(r_2+pL_2)i_2=E\sin(\omega t+\alpha) \quad (8)$$

$$i_1=i_2+i_m$$

The solution of these equations may be obtained either by using operational methods or by using the ordinary methods of solving differential equations, but the resulting expressions become rather cumbersome if all the terms are included. However, a simplification is possible since in practical motors the stator and rotor leakage inductances L_1 and L_2 are very small in comparison with the mutual inductance M, and hence may be neglected in certain expressions.*

The following boundary conditions hold:

at time $t=0$, $i_1=0$, $i_m=0$

and since no current is present when $t=0$

$$L_1pi_1+Mpi_m=E\sin\alpha$$

$$L_2pi_2-Mpi_m=0$$

In this manner we find:

$$i_1=I'\{(\sin\phi\cos\alpha-\cos\phi\sin\alpha)\epsilon^{-\lambda_2 t}+\sin(\omega t+\alpha-\phi)\} \quad (9)$$

$$i_m=I_m'[\epsilon^{-\lambda_1 t}\cos\alpha-\cos(\omega t+\alpha)] \quad (10)$$

The instantaneous electrical torque is obtained from equation 1. Two cases are assumed as follows:

Case I. Simultaneous application of voltage to both axes.

Case II. Application of voltage to β axis 90 degrees later than α axis to simulate effect of bouncing of switch contacts or irregularity in voltage application.

In practice it will be found almost impossible to apply voltage to all three phases at exactly the same instant; on the other hand the assumption of a 90-degree phase difference between voltage application to the two axes probably represents a fairly severe condition.

* An integration of these equations in which no terms were neglected has been carried out by E. H. Moss using numerical values for the constants M, L_1, and L_2 corresponding to an actual motor. This showed close agreement with the approximate method described.

Case I—Simultaneous Application of Voltage to Both Axes

In this case we use equations 9 and 10 taking $\alpha=0$ for the α axis and $\alpha=90$ degrees for β axis. Thus $i_{1\alpha}$ and $i_{m\alpha}$ are found from these equations by taking $\alpha=0$; $i_{1\beta}$ and $i_{m\beta}$ by taking $\alpha=90$ degrees. Using the expressions for $i_{1\alpha}$, $i_{m\alpha}$, $i_{1\beta}$, $i_{m\beta}$ thus found in (1) we obtain for the torque:

$$T_1=T_s\left\{1+\epsilon^{-\lambda_2 t}-\frac{\epsilon^{-\lambda_2 t}\cos(\omega t+\phi)+\epsilon^{-\lambda_1 t}\cos(\omega t-\phi)}{\cos\phi}\right\} \quad (11)$$

Case II—Application of Voltage to β Axis 90° Later Than on α Axis to Simulate Effect of Bouncing of Contacts or Irregularity in Voltage Application

In this case we again use equations 9 and 10 and assume that the switch is thrown on the β axis 90 degrees later than on the α axis. Let t = time measured from instant switch is thrown on the α axis and t_1 = time measured from instant switch is thrown on the β axis; then

$$t=t_1+\frac{\pi}{2\omega}$$

On the α axis we take $\alpha=0$ and $t=t_1+\pi/2\omega$ in equations 9 and 10 and thus obtain expressions for $i_{1\alpha}$ and $i_{m\alpha}$ in terms of t_1. The currents $i_1{}^\beta$ and $i_{m\beta}$ on the β axis will be obtained from the same equations in this case by taking $\alpha=180$ degrees and $t=t_1$ to take into account the fact that there is a phase difference of 90 degrees between the voltages and a lag of 90 degrees between the time the switch is thrown on the two axes. Using these values of $i_{1\alpha}$, $i_{m\alpha}$, $i_{1\beta}$, and $i_{m\beta}$ in equation 1 the following expression for the electrical torque T_2 is obtained in terms of the time t_1:

$$T_2=T_s\left\{1+\tan\phi\left[(1-c)\epsilon^{-\lambda_2 t_1}+(\sqrt{1+c^2})\epsilon^{-\lambda_2 t_1}\sin(\omega t_1+\alpha_1)\right]+\frac{\sqrt{2}}{\cos\phi}\epsilon^{-\lambda_1 t_1}\sin\left(\omega t_1-\phi-\frac{\pi}{4}\right)\right\} \quad (12)$$

where

$$c=\epsilon^{-\frac{\lambda_2\pi}{2\omega}} \text{ and } \alpha_1=\tan^{-1}c.$$

Nomenclature

$\cos\phi=\dfrac{r}{\sqrt{x^2+r^2}}$ = locked power factor

E = maximum value of applied voltage per phase

$f(\theta)$ = function representing torque-angle characteristic of shaft-coupling system

i_1, i_2 = stator and rotor phase currents

i_m = magnetizing current per phase

$i_{1\alpha}$, $i_{m\alpha}$ = stator and magnetizing currents on α axis

$i_{1\beta}$, $i_{m\beta}$ = stator and magnetizing currents on β axis

I' = peak value of steady-state locked stator current

I_m' = peak value of steady-state magnetizing current with rotor locked

I_m, I_r = moments of inertia of motor and driven load respectively

$I_e=I_mI_r/(I_m+I_r)$ = equivalent moment of inertia of rotor-coupling-load system

k = spring constant of shaft-coupling system

L_1, L_2 = stator and rotor leakage inductances per phase

M = mutual or magnetizing inductance

$p=d/dt$ = derivative operator

r_1, r_2 = stator and rotor resistances per phase

$r=r_1+r_2$

T_1 = electrical torque assuming simultaneous voltage application on α and β axes

T_{1m} = maximum electrical torque assuming simultaneous voltage application

T_2 = electrical torque assuming voltage application on β axis 90 degrees later than on α axis

T_{2m} = maximum electrical torque assuming voltage application on β axis 90 degrees later than on α axis

T_m = peak shaft torque or electrical torque

T_s = nominal starting torque

T = shaft torque

t = time

$\omega=2\pi$ times frequency of applied voltage

$\omega_n=2\pi$ times natural frequency of system consisting of motor rotor, coupling, and load

$x=x_1+x_2$

x_1, x_2 = stator and rotor leakage reactances per phase

x_m = magnetizing reactance

λ_1, λ_2 = decrement factors. $\lambda_1=\dfrac{\omega r_1 r_2}{x_m r}$; $\lambda_2=\dfrac{\omega r}{x}$

θ = angular twist of shaft-coupling system between motor and load

β_1, β_2, β_3, β_4 = transient shaft-torque components

γ_2, γ_3, γ_4 = phase angles of corresponding transient shaft-torque components

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

A High-Speed Differential Relay for Generator Protection

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ASSOCIATE AIEE

RECENT papers have shown that high-speed differential relaying is considerably complicated by the presence of the d-c transient in asymmetrical through fault currents. This is particularly true of generator differential relaying, since an asymmetrical fault near the terminals of a generator provides a more severe d-c transient than at any other point on the system. The effect of the d-c component is to produce a false differential current during a through fault because of dissimilar performance of the current transformers, even though they may nominally be duplicate. When this false differential current reaches tripping proportions with respect to the restraining current, even for as short a time as one cycle with a high-speed relay, the relay problem becomes one of properly discriminating between a false and a true differential current of tripping magnitude.

Means have been provided in the relay described in this paper to make the above discrimination. The solution has been worked out in accordance with two general principles. First, the principle of variable-ratio characteristics has been used. This principle was first described in a paper[1] presented at the 1939 winter convention, wherein it is shown that when the restraining current is large, corresponding to a heavy external fault, the sensitivity of the relay should be reduced to allow for greater shortcomings in current-transformer performance. Second, both theory and tests have shown that when current-transformer saturation occurs, the false differential current tends to be out of phase with the restraining current. Consequently, the new relay has been made less sensitive at the higher restraint values when the differential current is out of phase with the restraining current. The new relay is shown in figure 1, together with the necessary external transformer. The relay and transformer together form a complete three-phase unit.

Principle of Operation

In order to analyze the principle of operation of the relay, a simplified diagram, showing the essential parts for one phase only, is desirable. This is shown in figure 2. The main current transformers on each side of the generator are shown connected to terminals 1, 2, and 3 of the transformer element which feeds the relay. The principal currents from the secondaries of the current transformers in the leads of the generator flow only in the external transformer, as will be noted in the diagram. The transformer element develops auxiliary current and voltage quantities for actuation of the relay element shown in the bottom part of the diagram. The relay element has been shown very schematically. It is composed of a balanced-beam element wherein the contacts are restrained from closing by split-phase voltage windings acting on the rear end of the beam, while the operating-coil magnetic circuit acting on the front end of the beam tends to close the contacts. Inspection of the transformer element of this diagram will show that it consists of two transformer elements, both on the same magnetic circuit. Coils A and B on the center leg of the punchings form one of these transformers, which will be referred to as the sum coil transformer, wherein a voltage is developed in winding B in response to the restraining currents, I_1 and I_3. Since the voltage developed by winding B energizes split-phase restraining coils as shown, it is evident at once that the restraining force on the back end of the beam will never pass through zero.

A possible difference current, I_2, is shown flowing in the differential connection of the main current transformers in the diagram. In the transformer element, this current must flow through the two primary coils, C_1 and C_2, of the second transformer unit on the magnetic core, this unit being referred to as the difference coil transformer. The coils, D_1 and D_2, form the secondary windings of this second unit. They are connected in series to energize the operating coil of the relay element.

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1. For numbered reference, see end of paper.

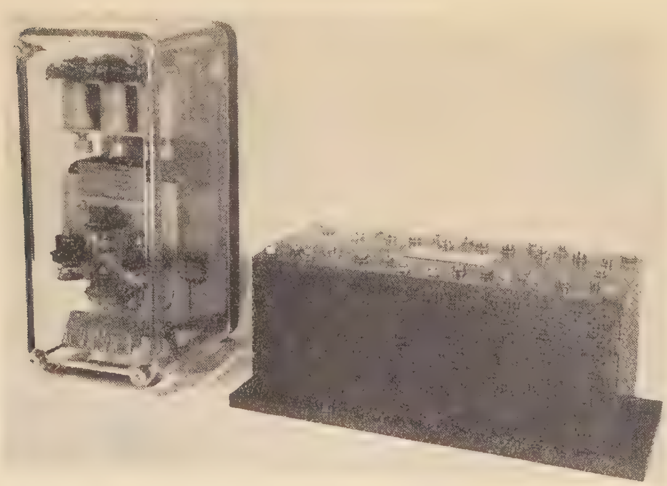


Figure 1 (left). Type HA ratio differential relay for generator protection

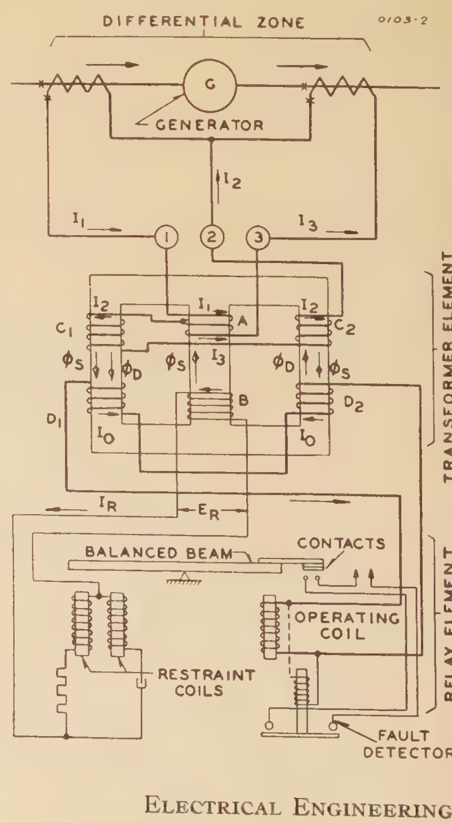


Figure 2. Schematic diagram of one relay element and auxiliary current transformer

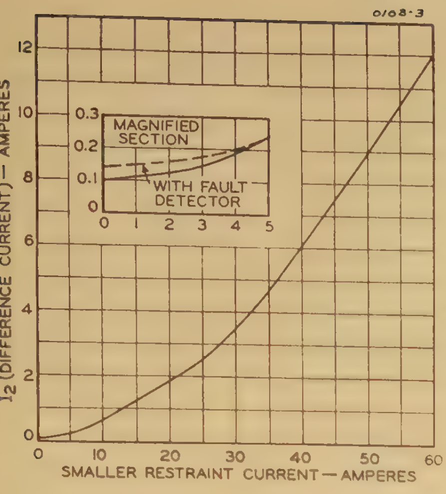


Figure 3. Typical operating characteristics of relay. Difference current, I_2, in phase with restraint current

Variable-Ratio Characteristics

Assuming in-phase currents, it will be seen from figure 2 that if the difference-coil current transformer is made to saturate to a greater extent at the higher currents than the sum-coil current transformer, and assuming linear relay characteristics, then it is obvious that a higher percentage of difference-coil current will be required to trip the relay contacts as the saturation of the difference-coil transformer is increased with respect to the sum-coil transformer. That is, as the restraint current is increased, the difference current to trip the relay will increase at a higher rate, thus resulting in the variable-ratio characteristic of figure 3. It will be noted from the curve that the minimum tripping current of the relay is 0.1 ampere in terms of the secondary, thus providing high sensitivity at no load on the machine. At 5 amperes restraint current, corresponding to full load, the difference current required to trip the relay is 0.25 ampere. This corresponds to a relay sensitivity of 5 per cent. From this point on, the variable-ratio characteristic of the relay is illustrated by the curve. For example, at 60 amperes restraint, a difference current to trip of 12 amperes represents 20 per cent unbalance. This indicates a decrease in sensitivity of the relay by a four-to-one range between normal and 12 times normal full-load current.

Phase-Angle Characteristics

Flux arrows have been drawn in the transformer element, figure 2, corresponding to the relative instantaneous direction of the currents, I_1, I_2, and I_3, as shown. The polarity of the connections of coils C_1, C_2, is such that ϕ_D, established by the difference current, I_2, flowing through coils, C_1 and C_2, circulates around the outer legs of the laminations. With symmetrical coil designs, there is no tendency for a portion of the flux, ϕ_D, to circulate through the middle leg of the transformer, since the two ends of this leg will be at the same magnetic potential with respect to ϕ_D. Thus, the flux, ϕ_D, established by the difference current, I_2, does not tend to establish directly a restraining-coil voltage, E_R, in coil B. The flux, ϕ_S, set up by the currents, I_1 and I_3, in coil A returning from top to bottom in the outer legs of the transformer as shown, has no tendency to induce operating-coil current in coils, D_1 and D_2, since, because of the polarity of connections of coils, D_1 and D_2, opposite voltages will be generated in these two coils by ϕ_S. From the above discussion,

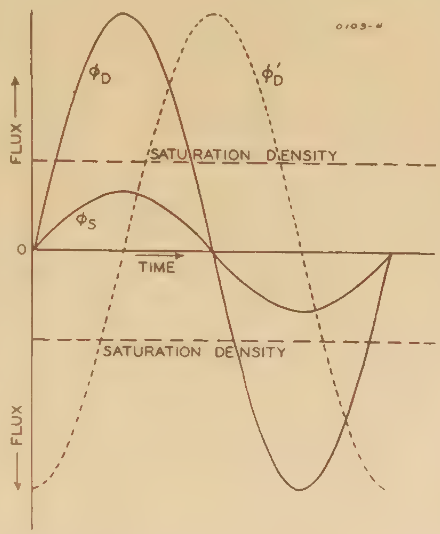


Figure 4. Flux waves in auxiliary current transformer

it is evident that if the magnetic material were of infinite permeability and never saturated regardless of the required flux density, the two transformer units, A/B and C_1C_2/D_1D_2 would have no effect upon each other and there would be no point to placing them both on the same magnetic structure. The fact that the magnetic material is not perfect, however, does introduce a mutual reaction between the two transformers, and this will be discussed.

Assume that the currents I_1, I_2, and I_3, of figure 2 are associated with the flux waves of figure 4, these flux waves being required to generate sufficient voltage in the respective coils to circulate the currents, I_0 and I_R, through the relay element. With I_2 in phase with I_1 and I_3, the power factor of the relay burden, both restraining and operating coils, may be so chosen that the fluxes, ϕ_S and ϕ_D, of figure 4 will be in phase as shown by the solid-line curves. If the quantities are so chosen, however, that the peak of the flux, ϕ_D, for the difference-current transformer, C_1C_2/D_1D_2, extends considerably into the zone of saturation, as shown in figure 4, then it will be noted that the peak flux, ϕ_S, for transformer A/B will be hard to obtain magnetically. That is, the return circuit for ϕ_S is the outer legs of the magnetic core in parallel, and these two outer legs are at that particular instant badly saturated by the difference transformer flux, ϕ_D. What this means is that a larger percentage of the sum-coil currents, I_1 and I_3, will go to magnetizing current, leaving a very small percentage to be transformed into restraining coil current, I_R, through the winding, B. (Casual inspection of figure 2 might indicate that the right-hand leg of the transformer punching might serve as a good return circuit for ϕ_S, since ϕ_S and ϕ_D are shown in opposite directions in this leg, thus reducing saturation and voiding the above argument. However, the argument is still valid, because at high saturation densities, there is not much difference between the amount of ampere turns required to reduce the flux density by a small increment and the amount of ampere turns to increase the flux density by the same small increment.) Thus, the solid-line flux, ϕ_S, of figure 4 is associated with a phase-angle condition in which it would be expected that the required difference current to trip the relay would be reduced because

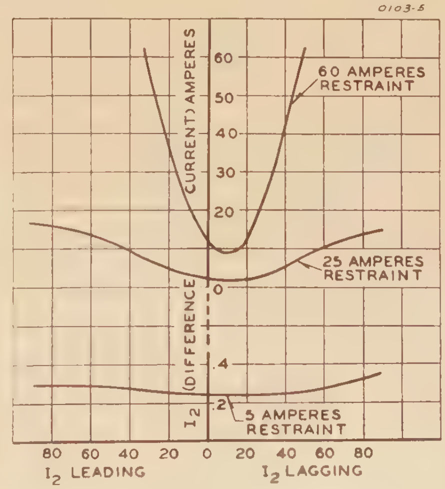


Figure 5. Typical phase-angle characteristics of relay

Phase angle in degrees of difference current with respect to smaller restraint current

of a reduced efficiency of the sum-coil transformer. If now the phase angle of the difference-coil current, I_2, is changed by 90 degrees with respect to the restraining current, I_1 and I_3, so that the difference-coil flux, ϕ_D, is moved by 90 degrees lagging, as shown by the broken-line curve, ϕ_D', of figure 4, it will be noted that the peak of sum-coil flux, ϕ_S, occurs at the instant that the difference-coil flux is passing through zero. It would be expected that under this condition the sum-coil transformer would operate more efficiently than in the previously described case, since the peak of its flux, ϕ_S, is more easily obtained when its return circuit is not saturated. The above discussion indicates that since the difference-coil transformer, through its flux requirements, is caused to saturate the return circuit for the sum-coil transformer, and since this saturation effect varies throughout the cycle, then the mutual reaction between the two transformers is variable, depending upon the phase-angle relationship between the sum-coil currents and the difference-coil current. By suitably proportioning the power factor and magnitude of the restraining-coil and operating-coil burdens of the relay element in conjunction with the transformer design, it was possible to arrive at a design in which the combination is less sensitive to difference-coil currents when these difference-coil currents are substantially out of phase with the restraining-coil currents.

The phase-angle characteristics of the relay are illustrated in figure 5. The curve shows that at 60 amperes restraint,

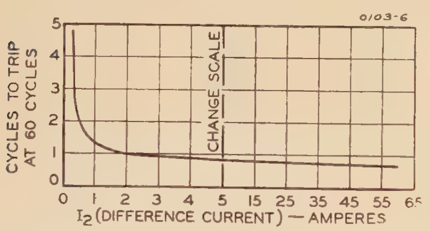


Figure 6. Typical current-time curve of relay. Smaller restraint current constant at five amperes (full load)

it is practically impossible to cause the relay to trip if the difference current is out of phase with the restraining current by more than 40 to 50 degrees. This provides a very large margin of safety in that the difference currents are likely to be highest when the restraining-coil current is the greatest, and they will also tend to be out of phase with the restraining-coil currents. At five amperes restraint, however, corresponding to full-load current, it should be noted that the phase-angle curve of the relay is substantially flat. This is desirable at load current, because there is no way of predicting just what the phase-angle relationship will be between a small internal fault current in a generator and the load current on the machine at the time.

When considering the phase-angle curves, it should be remembered that those curves where the restraint current exceeds 5 amperes represent through short-circuit conditions. For this reason, there is no cause for alarm in the indication that, for example, a 40-ampere differential current at 60 degrees lagging would not trip the relay at 60 amperes restraint. It would be impossible to obtain an internal short-circuit of 40 amperes magnitude and maintain a through current of 60 amperes for an external fault. In other words, these curves, except for the 5-ampere restraint curve, apply only to through fault conditions, and are not applicable to internal fault conditions without proper interpretation of the effect of the sum-coil currents. For example, the 60-ampere restraint curve referred to was taken with a setup in which the sum-coil current directions agreed with those shown in figure 2, these representing an external fault. That is, the sum-coil ampere turns produced by the currents, I_1 and I_3, were additive and produced a positive restraining force on the relay element. If it is now assumed that a fault within the differential zone draws 60 amperes (secondary) through the generator, and an additional 60 amperes back-feed from the bus, it is immediately obvious that the direction of the two currents, I_1 and I_3, will be reversed with respect to each other, their ampere turns will cancel in the sum-coil transformer, and there will be no restraint. Hence, the curve does not apply. For another example, let it be assumed that for the same internal fault, the generator current, I_1, is 60 amperes, but that the back-feed current I_3 reversed, is increased to 180 amperes. Then 60 amperes in one-half of the sum coil winding will cancel the effect of 60 amperes of the 180 amperes in the other half, leaving a net effect of 120 amperes in half of the winding, equivalent in effect to 60 amperes flowing in one coil and out of the other, as shown in figure 2. In this case, then, the 60-ampere curve of figure 5 would apply, although it should be remembered that the difference-coil current would be definitely fixed as the sum of the 60- and 180-ampere currents. This sum could conceivably be somewhat out of phase with the net restraining-coil current, but not enough to affect positive

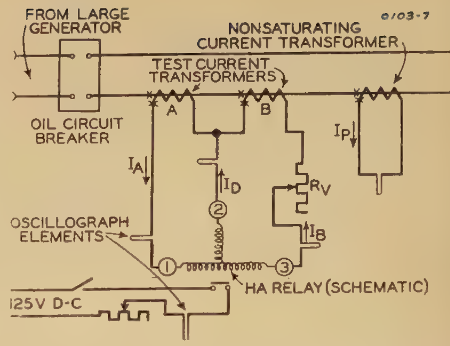


Figure 7. Schematic diagram of test connections

R_v represents a variable resistor used to produce more severe saturation in current transformer B

relay operation. Referring back to the curve for 5 amperes restraint, figure 5, it is possible that a light internal fault might occur which would not disturb the normal through load current of 5 amperes to any great extent, hence, this curve is applicable for internal faults as stated.

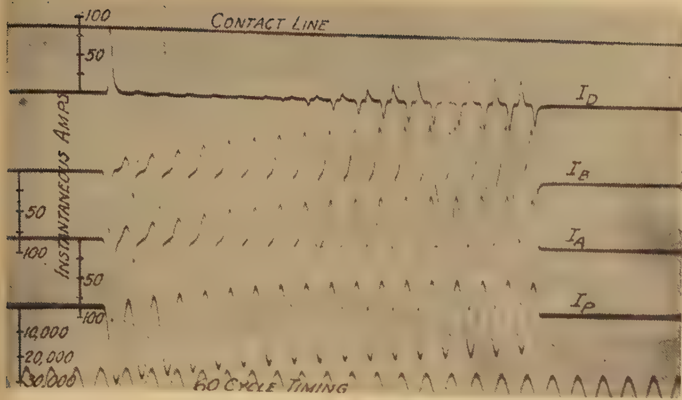
The time of operation of the relay is shown by the current-time curve of figure 6, wherein it is shown that the relay is a one-cycle relay.

Fault Detectors

The relay is provided with three small solenoid-type fault detectors, one for each of the elements, which may be used for those locations where the switchboard panel is subject to heavy jars or vibrations. At very light loads, the restraint occasioned by the load current may be negligible, and the extreme sensitivity of the differential element renders it subject to momentary closing of the contacts because of jars to the panel. In order to eliminate false tripping from this cause, the fault detectors are provided. Their coils are connected in parallel with the operating coils, and their contacts in series with the differential element contacts. Use of the fault detectors increases the minimum tripping current to 0.14 ampere, but has a negligible effect on the rest of the operating characteristics, figure 3.

Confirming Tests

Suitable tests have been made on the relay described. The essentials of the test connections are shown in figure 7. A large generator was used, so that d-c time constants up to $T_a=0.14$ were obtained. The resistor, R_v, of figure 7 was used to increase the burden on test transformer B so that the two transformers under test might be deliberately



Primary current, 10,800 amperes rms a-c component, T_a=0.11 second

Test transformer A: 1,000/5, 2.7 square inches iron; secondary circuit resistance —1.36 ohms

Test transformer B: 1,000/5, 2.53 square inches iron; secondary circuit resistance—4.04 ohms

Figure 8. Test oscillogram for external fault

unbalanced until failure of the relay occurred.

Figures 8 to 11 are typical oscillograms from a large number of tests. The essential data for each of these oscillograms are given in the captions.

In figure 8, representing an external fault, it is to be noted that there is an initial high peak of differential current which scales 87 amperes maximum instantaneous value. The normal output of transformers A and B would have been 54 amperes rms a-c component, if they held their ratio. Inspection of the traces representing the output of current transformers A and B reveals, however, that they do not hold their ratio, and that their output is severely limited by d-c saturation for the first few cycles. On this basis, it is obvious that the high-speed relay sustained a very high percentage unbalance for one peak without tripping, as the relay contact line indicates. A simple high-speed ratio-differential relay with the usual current coils would have tripped under this condition.

The peculiar wave shape of the differential current, shown in figure 8, warrants some discussion. The initial high peak is caused by the fact that current transformer B became thoroughly saturated by the d-c component a short interval of time before current transformer A became saturated. During the interval between the complete saturation of transformer B and transformer A, when transformer B alone was breaking down in ratio, transformer A was able to force the peak of differential current through the relay. When saturation was reached in both transformers, however, both of them performed very much as if they were air-core transformers, neither of them having sufficient capacity to hold their ratio with the burdens involved. During the time when both transformers were saturated, both the reduced capacity of the better current transformer as well as the impedance of the differential circuit effectively reduced the magnitude of the differential current. Thus, it will be noted that the difference current is inconsequential for approximately eight cycles after the initial high peak. After approximately eight cycles however, transformer A, having a better ratio of iron area to resistance burden, began the process of recovery from d-c saturation so that it was again able to perform somewhat better than transformer B. For this reason, a current began to reappear in the differential circuit.

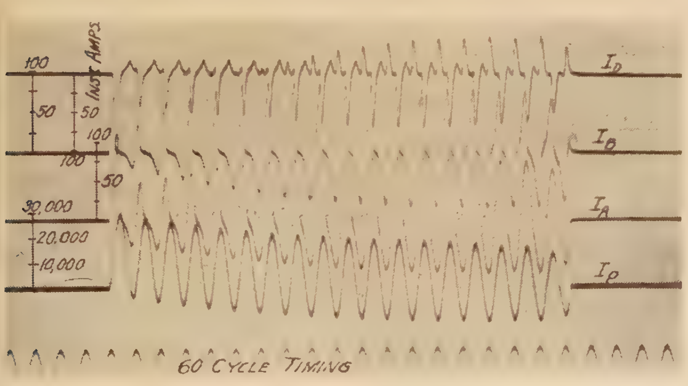


Figure 9. Test oscillogram for external fault

Conditions the same as for figure 8, except that the relay was short-circuited, terminal 1 to 2 to 3 (figure 7)

As has been stated, the nominal output of both transformers would have been 54 amperes rms secondary, a-c component, if neither transformer had saturated, this value being derived from the 10,800-ampere symmetrical a-c component of the primary current and the ratio of the current transformers. In order to force this secondary current through the resistance burdens indicated, transformer B would have had to develop a flux density of 160,000 lines per square inch, and transformer A would have had to develop 51,000 lines of flux per square inch, calculated from the equation:

$$B_m = \frac{IR\,10^8}{4.44nfA}$$

where

B_m = maximum flux density in lines per square inch
n = number of secondary turns
f = frequency in cycles per second
A = cross-sectional area of the iron core in square inches
I = rms secondary amperes
R = total secondary circuit resistance

(This equation has been derived from the familiar transformer equation, $E = 4.44nf\phi_m 10^{-8}$.) The flux density values indicated form a measure of the unbalance between the two current transformers, the flux densities for perfect a-c performance having a ratio of 3.14/1.

The wave form of the differential current in figure 8 was of sufficient interest to arouse speculation concerning what this differential current would look like if the impedance of the relay circuit were zero. In order to obtain data on this point, all three terminals of the relay were short-circuited together and the oscillogram of figure 9 was taken under the same conditions. (No contact line was desired in this case, since the relay element was short-circuited.) Figure 9 shows a similar high initial peak of differential current, which scales 101 amperes. Since there was no differential circuit impedance in this test to form a balancing action between the two transformers, the differential current did not subside to almost zero for several cycles, as in figure 8. The calibration of the oscillograph was the same for both tests.

Figure 10 is an oscillogram for an internal fault with values as given in the caption. The internal fault was simulated by reversing the secondary connections of transformer B so that the total current of both transformers passed through the differential circuit of the relay. The time of operation of the relay is scaled from the contact line of the film to be approximately 0.6 cycle. Again, there was considerable saturation of the current transformers, particularly because of the d-c transient, yet prompt

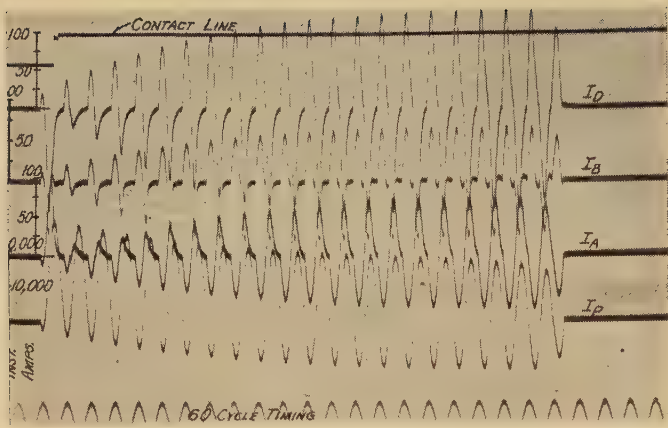


Figure 10. Test oscillogram for internal fault

Primary current, 10,900 amperes rms a-c component, $T_a = 0.123$ second

Test transformers as in figure 8 except secondary circuit resistance for current transformer B reduced to 2.44 ohms

operation of the relay was not affected.

Figure 11 shows another test for an external fault except that a different pair of current transformers was used with a different degree of unbalance, particularly with regard to the cross-sectional area of the iron in the test transformers. In this case, the calculated flux requirements for the a-c symmetrical component alone are as follows:

Transformer A—7,100 lines per square inch
Transformer B—71,600 lines per square inch

$$\text{Ratio } B/A = \frac{71{,}600}{7{,}100} = 10.2/1$$

In figure 11, the time of the first peak of differential current has been indicated by the dotted line, a, and it will be noted that this peak occurs earlier than the peaks of the two restraint, or sum coil, currents as indicated at b. This illustrates the meaning of the statement previously made that the differential current tends to be out of phase with the restraint current when the current transformers saturate during through fault conditions.

Summary of Test Results

The tests were made over a wide range of variation between current-transformer designs and loading, as has been indicated in part in figures 8 and 11. The purpose of this was to explore the range of possibilities of the new relay by exceeding the range normally to be expected. For example, it is felt that the conditions of figure 8 are more severe than would normally be expected for a reasonable application of generator differential protection. That is, it appears that the extreme importance of a large generator would justify the application of transformers whose a-c flux requirements for the maximum symmetrical external fault would not exceed the nominal saturation density of approximately 70,000 lines per square inch. Other tests, not described here, were made to cover the conditions imposed when a generator is connected to a double bus through two circuit breakers. In such an application, a heavy current may flow during an external fault from one bus to the other through the two circuit breakers connected to the generator. Such a current, flowing through the two current transformers per phase on the bus side of the generator, would materially increase the duty on them as compared to the duty imposed upon the current transformers in the neutral connection of the machine being protected. The relay performed satisfactorily in these tests.

Since it is obvious that there is a myriad of possibilities between different applications with regard to slight unbalances in iron area and secondary burden in current transformer circuits, the problem is how to best express the permissible variation in general terms. It has been found that the method of analysis used for the test of figures 8 and 11 is the most suitable; that is, where the flux density of the transformer is calculated showing the requirements for the maximum symmetrical current which will be experienced for an external fault. This method gives at once a figure which takes into consideration the factors which tend to unbalance the current-transformer performance for a given application.

A wide variation in permissible loading has been shown by the ratios of calculated flux densities of 3.14/1 for figure 8, and 10.2/1 for figure 11. In general, it was found that a higher ratio was permissible when the maximum calculated flux density for either transformer did not greatly exceed the nominal saturation density of approximately 70,000 lines per square inch.

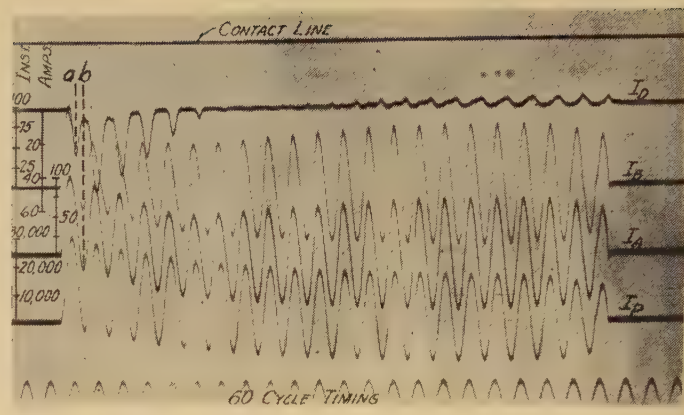


Figure 11. Test oscillogram for external fault

Primary current, 11,000 amperes rms a-c component, $T_a = 0.094$ second

Test transformer A: 4 primary, 800 secondary turns, 1,000/5, 4.8 square inches iron; secondary resistance (total) 1.31 ohms

Test transformer B: 1 primary, 200 secondary turns, 1,000/5, 1.7 square inches iron; secondary resistance (total) 1.18 ohms

Conclusions

1. In the past, the application of high-speed (one-cycle) differential protection to generators has required the closest scrutiny of the current-transformer characteristics with respect to the duty imposed. This study involved particular attention to the effect of the d-c component of asymmetrical through faults. In all such cases, careful matching of current-transformer characteristics was required.

2. With the new relay, it suffices to look carefully only at the a-c characteristics of the transformers. The application is thus reduced to the simplicity of the older, slower-speed, induction-type relay, where a consideration of the a-c characteristics of the current transformers was generally sufficient.

3. A means of comparing the duty on the current transformers has been given through the method of calculating the theoretical maximum flux density required for the a-c component. When the resulting figure does not materially exceed the nominal saturation value of 70,000 lines per square inch, an allowable ratio between the values for the two current transformers of 3/1 provides ample safety factor to guarantee satisfactory relay operation.

Reference

1. CONSIDERATIONS IN APPLYING RATIO DIFFERENTIAL RELAYS FOR BUS PROTECTION, Smith, Sonnemann, and Dodds. AIEE TRANSACTIONS, volume 58, June 1939.

Discussion

Discussion will be found in the 1940 annual TRANSACTIONS volume and in the 1940 "Transactions Supplement" to ELECTRICAL ENGINEERING.

Frequency Modulation

W. L. EVERITT
FELLOW AIEE

RADIO communication makes use of a medium common to the whole world for the transmission of many signals simultaneously. In order to accomplish this a high-frequency electromagnetic wave has one of its characteristics varied in accordance with the instantaneous variations of the signal to be transmitted. The control of these variations is called modulation. The various simultaneous messages can then be separated by:

(*a*). Differences in the frequency band used.

(*b*). Differences in signal strength.

(*c*). Differences in direction of the source.

The allocation of frequencies and geographic location to stations engaged in different services is now a matter of legislation and international agreement. This regulation is necessary in order to reduce interference to a minimum.

The range of a radio station is limited solely by the point at which undesired interference reduces the quality of the received signal below a certain minimum. The amount of interference which may be tolerated differs with different classes of service, for instance, it would be less on a broadcast program designed to produce pleasure, than on a communication service designed to convey intelligence.

There are five principal sources of interference to radio reception. They are:

(*a*). Interference from other radio stations.

(*b*). Interference from natural electrical disturbances such as thunderstorms (static).

(*c*). Interference from electrical equipment not intended for radio purposes.

(*d*). Interference between identical signals traveling from the station originating the desired signal, but over two different paths. Since radio waves are alternating phenomena resolvable into a band of frequencies, the addition of two similar signals traveling over different paths must take account of both magnitude and phase. Distortion in the resultant signal may result due to the varying phase relations between the components with the same frequency in the two signals. One of the paths is usually caused by reflection from some medium such as the ionosphere. If this path varies in length with time, fading will result. When this produces distortion the phenomenon is called selective fading.

(*e*). Interference from random noise produced in the receiver by fluctuations in the motion of the electrons in the early stages of the amplifiers.

The major problems of the radio engineer are:

I. To obtain the maximum range at the minimum cost.

II. To secure the desired quality in the reproduction of signals.

Because the range is determined by the interference, and the quality is greatly affected by it, the reduction of interference becomes of paramount importance.

The reduction of interference must be accomplished by making use of some characteristic which differentiates the desired signal to a greater or less extent from the undesired interference. Four methods of differentiation have been extensively used. Each method in turn has its limitations. These methods and their limitations are:

1. Use of high power in the transmitter so that the strength of the desired signal will dominate the undesired.

This method is limited by the cost of high powered transmitters and by the interference it introduces to other services. Furthermore it does not affect selective fading since both signals (coming over two paths) are increased by the same amount.

2. Increasing the modulation of the radio wave to the greatest possible value.

This method is limited in amplitude modulation because it is not possible to vary the magnitude of a radio wave by more than 100 per cent and interfering signals, including static, will in general be modulated by similar amounts.

3. Use of selective circuits in the receiver so that only energy in the narrow band of frequencies which includes the desired signal will be received.

This method is limited because a definite band width is necessary for any given quality of reproduction and within this band there may be some portion of the energy in the spectrum of the interference.

4. Use of directive antennas at the receiver so that it is most sensitive to electromagnetic waves coming from the direction of the transmitter creating the desired signal and is insensitive to radiations originating in other directions.

This method is limited by the expense of directional antennas and by the fact that some interference may be originating in the same direction as the desired signal.

It is apparent that the methods just mentioned, taken individually or in combination, do not offer a complete solution of the problem. In fact no complete solution would appear possible, as the ultimate range of any transmission must be determined by the tolerable interference. However, any method which offers increased possibilities in the differentiation between desired signal and interference may be used to improve transmission. *Frequency modulation* offers such an additional method by which interference may be separated from the desired signal and it is the purpose of this paper to outline the principles and practices by which this may be accomplished.

The use and study of frequency modulation is not new. The Poulsen arc, developed before 1914, transmitted continuous-wave telegraph signals in which the frequency was shifted from one value to another when the key was depressed. Carson[1] and Roder[2] made theoretical investigations of the effects of frequency modulation on the spectrum of the modulated wave. Carson's investigation was

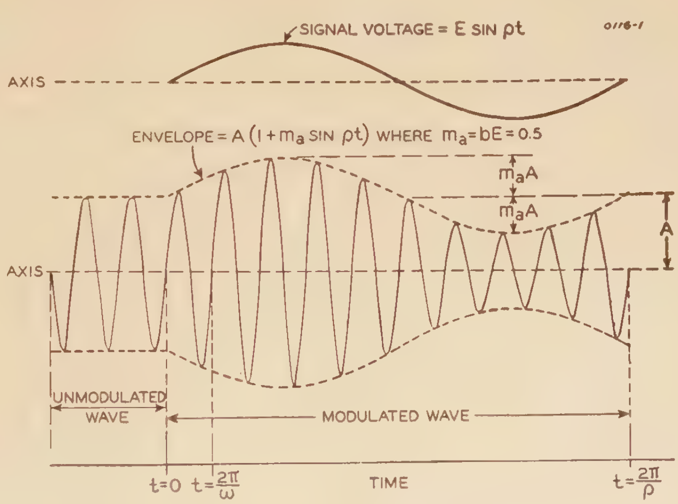


Figure 1. An amplitude - modulated wave

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1. For all numbered references, see list at end of paper.

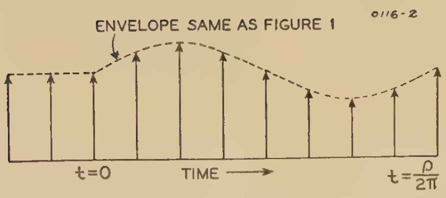


Figure 2. Vector diagrams of the amplitude-modulated wave of figure 1 for successive instants

made to analyze the proposal that frequency modulation could be used to reduce the band width required for a given signal. He proved that, on the contrary, frequency modulation never reduced the band width and might greatly increase it. Mathematics provides a correct answer to questions which are asked by its means, but it cannot be expected to provide answers to questions which are not asked. What was overlooked in the early mathematical analyses was the fact, later demonstrated by Armstrong,[3] and subsequently by Carson[4] and Fry, that frequency modulation provides an important method of distinguishing between desired and undesired signals which occupy the same portion of the frequency spectrum.

It will be necessary to go into some details of the principles of frequency modulation in order to show the reasons for this effect.

Modulation

Modulation of a radio wave is the process by which some characteristic of the radio wave is varied in accordance with the time variation of a signal, such as the instantaneous variations associated with speech, music, or the manipulation of a telegraph key. A general alternating wave may be represented by the equation

$$e = A \sin\theta \qquad (1)$$

where θ is given by the relation

$$\theta = \omega t + \phi \qquad (1a)$$

and so

$$e = A \sin(\omega t + \phi) \qquad (1b)$$

(In this discussion the word "wave" will be used in one of its accepted meanings to denote a repetitive phenomenon.)

Two groups of modulation methods are recognized.

1. Amplitude modulation where A is varied by the signal.
2. Angular modulation where ϕ is varied by the signal.

(Frequency modulation is a special form of angular modulation.)

Amplitude Modulation

In an amplitude-modulated wave the amplitude is varied about its mean value in proportion to the signal. Let the original signal (such as the sound pressure on the microphone) be represented by the function $f(t)$. Then the amplitude factor A of equation 1*b* is modified by $f(t)$ to give the amplitude-modulated wave

$$e = A[1 + bf(t)] \sin(\omega t + \phi) \qquad (2)$$

where b is a factor determined by the design and operation of the modulating system and has dimensions such that $[bf(t)]$ is a pure numeric. b is usually a constant, but in some cases it is made a function of audio frequency. For example, if it is made to change with frequency in the proper manner compensation may be secured for defects in the frequency characteristic of some other part of the system.

The amplitude variation cannot carry the amplitude below zero. Therefore the factor b should be so chosen by the operator that $[1 + bf(t)]$ never becomes negative. Therefore $[bf(t)]$ should not exceed an absolute value of unity. This absolute value of the maximum of $[bf(t)]$ is called the amplitude *modulation factor* and is given the notation m_a.

If the signal $f(t)$ is sinusoidal with a frequency $\rho/2\pi$, equation 2 becomes

$$e = A(1 + m_a \sin \rho t) \sin \omega t \qquad (3)$$

The curve of equation 3 is illustrated in figure 1 for $m = 0.5$ and $\omega/\rho = 10$. It will be noted that the wave crosses the axis at regular time intervals of $2\pi/\omega$ seconds for both the modulated and unmodulated waves.

In alternating phenomena a single frequency is represented by the projection of a vector of constant length rotating with the constant angular velocity $\omega = 2\pi f$. The wave of equation 2 could also be represented by a vector rotating with a constant angular velocity ω, but the length of the vector would be changing at a low frequency rate as given by the equation

$$\text{Length of vector} = A[1 + bf(t)] \qquad (4)$$

The term $A[1 + bf(t)]$ is called the *envelope* of the wave. In equation 3 the envelope would be $A[1 + m_a \sin \rho t]$ as is illustrated in figure 1.

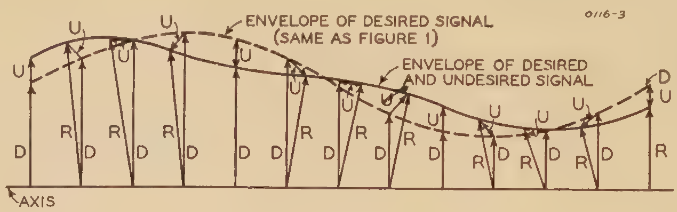


Figure 3. Interference with an amplitude - modulated wave of a carrier of slightly different frequency

D—Vector of desired signal
U—Vector of undesired or interfering signal
R—Resultant vector $(D+U)$ of sum of desired and undesired signals

In drawing vectors which represent alternating phenomena it is common practice to consider that the observer is traveling on a platform which is also rotating about the same center with a velocity ω. The original vector would then appear to be stationary and could be represented by a single drawing. However, if either the magnitude or the phase of the vector is changing with time, a series of successive drawings is necessary to illustrate what is happening.

These successive drawings of stationary vectors for the wave of figure 1 are shown in figure 2 for time intervals of one-eighth the period of the low-frequency wave producing the modulation.

At the receiver the detector produces a response which is proportional to the envelope of the modulated wave (except for the constant component).

Interference of Two Amplitude-Modulated Waves

If a second amplitude-modulated wave of the same carrier frequency and phase is added to the wave of figure 1 the resultant wave will have an envelope which is the sum of the envelopes of the two waves, for the vectors will be adding in phase. The interfering effect will be noticeable if the undesired signal is as much as one per cent of the desired signal. Hence it is desirable to make the value of m_a as large as possible, since the operator of a given communication system cannot control the modulation of the interfering wave with the undesired signal.

If the frequency of the interfering wave is slightly different from the desired wave (the difference being too small to eliminate it by selective circuits) then the interfering wave will produce a variation in the envelope which variation has an amplitude equal to the magnitude of the interfering wave (even if it is unmodulated). This additional variation will occur at a frequency which is equal to the difference

between the carrier frequencies of the desired and undesired signals, and will produce a squeal which is further superimposed on the resultant envelope. This is illustrated by the vector diagrams in figure 3, where the undesired signal has a frequency which exceeds the frequency of the desired signal by $1.5\rho/2\pi$. It is seen that the resultant envelope is modified by an additional component equal to the magnitude of the undesired wave, and so introduces interference proportional to the magnitude of the interfering wave.

Again it is apparent that the amplitude of the envelope of the desired signal should be kept as large as possible in order that the interference may be minimized. If equation 2 represents current or voltage, the amplitude of the envelope may be increased by increasing either the power or the amount of modulation (m_a).

Angular Modulation

In angular modulation (of which frequency modulation is a subdivision) the angle ϕ of equation 1*b* is given by a function of time which is related, but not in all cases, directly proportional, to the signal function $f(t)$. The two principal subdivisions of angular modulation which

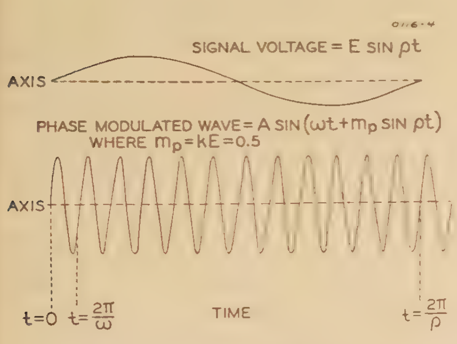


Figure 4. An angular-modulated wave

The 1st, 4th, 7th, 10th, and 13th cycles are shown in detail in figure 5

have been extensively studied are phase modulation and frequency modulation.

(*a*). Phase Modulation

In this type of modulation the phase angle ϕ is made to vary in accordance with the signal. That is

$$\phi = b_1 f(t) \tag{5}$$

where b_1 is a *constant* determined by the design and operation of the modulating system. When equation 5 is inserted in equation 1*b* the wave becomes

$$e = A \sin\,[\omega t + b_1 f(t)] \tag{6}$$

The maximum value of $b_1 f(t)$ is called the *phase modulation factor* m_p. It is the maximum number of radians by which the phase of the carrier is altered during modulation. If the signal is sinusoidal with a frequency $\rho/2\pi$, equation 6 becomes

$$e = A \sin\,[\omega t + m_p \sin \rho t] \tag{7}$$

(*b*). Frequency Modulation

In this type of modulation the *instantaneous frequency* is varied about the average value $\omega/2\pi$ in proportion to the instantaneous value of the signal. By definition, the use of the word "frequency" is extended to the general equations 1 and 1*b* by the relation

$$2\pi f_{\text{inst}} = \frac{d\theta}{dt} = \omega + \frac{d\phi}{dt} \tag{8}$$

Since ω is a constant (2π times the carrier frequency) the signal must modify $d\phi/dt$ so that the instantaneous frequency is given by the relation

$$f_{\text{inst}} = \frac{\omega}{2\pi} + b_2 f(t) \tag{9}$$

where b_2 is a design and operating constant. The maximum value of $b_2 f(t)$ is the maximum deviation in instantaneous frequency of the modulated wave from the unmodulated one and is called the *frequency modulation factor*, or frequency deviation, m_f. If $f(t)$ is a sine wave with a frequency $\rho/2\pi$ then

$$b_2 f(t) = m_f \sin \rho t \tag{10}$$

If equation 10 is combined with equations 8 and 9

$$2\pi f_{\text{inst}} = \omega + 2\pi m_f \sin \rho t = \omega + \frac{d\phi}{dt}$$

which gives

$$\phi = \int 2\pi m_f \sin \rho t dt = -\frac{m_f}{f_\rho} \cos \rho t$$

where f is the frequency of the modulating signal. If this phase angle is inserted in equation 1*b* the result will be

$$e = A \sin\left[\omega t - \frac{m_f}{f_\rho} \cos \rho t\right] \tag{11}$$

Equations 11 and 7, which apply to a signal with a single frequency, do not differ appreciably (except for a 90-degree shift in the modulation phase). In equation 11 the maximum shift in phase (corresponding to the phase modulation factor m_p) will be

$$m_p = \frac{m_f}{f_\rho} \tag{12}$$

where m_f is the frequency deviation and f_ρ the modulating audio frequency. The value of m_f when f_ρ is the maximum audio or signal frequency to be transmitted is called the *deviation ratio.*

m_p in phase modulation and m_f in frequency modulation are arbitrary design factors. Unlike amplitude modulation they are not restricted to a maximum value of unity, for m_p may be hundreds of radians or m_f thousands of cycles per second if desired. The limitations on m_p and m_f will be determined by the allowable frequency spectrum and will be discussed later.

The distinction between phase and frequency modulation is as follows: if the frequency, but not the intensity of the modulating signal changes

m_p is constant in phase modulation.

m_f is constant in frequency modulation.

It follows from equation 12 that in frequency modulation the phase deviation m_p is inversely proportional to the modulating frequency. On the other hand in phase modulation the frequency deviation is directly proportional to the modulating frequency.

Figure 4 is an illustration of the angular modulation as represented by equation 7 for the case where $m_p = 0.5$ and $\omega/\rho = 12$. On a casual examination this would appear to be a single frequency wave. However, the intervals at which it crosses the axis vary throughout the audio cycle. In order to show this the 1st, 4th, 7th, 10th, and 13th cycles are expanded and shown in figure 5. It is seen that the varying shift in phase also produces a change in frequency which varies throughout the low-frequency cycle.

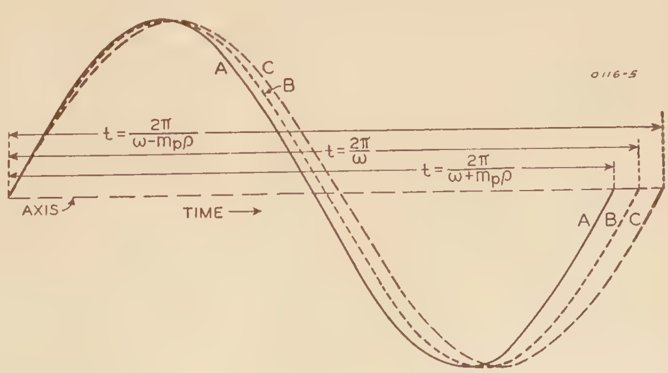


Figure 5. Expansion of individual cycles in figure 4

A—1st and 13th cycles of figure 4

B—4th and 10th cycles of figure 4

C—7th cycle of figure 4

The successive vector diagrams for the angular-modulated wave of figure 4 (corresponding to the diagrams of figure 2 for an amplitude-modulated wave) are shown in figure 6. The signal wave is included for identification of the various instants.

The difference between phase and frequency modulation may be illustrated by the way the motion of the resultant vector would appear to an observer riding with the carrier vector. In phase modulation, two audio signals of equal amplitude, but of different frequencies, would produce equal angular *amplitudes* in the apparent swing of the resultant vector. In frequency modulation two audio signals of equal amplitude would produce equal maximum angular *velocities* in the apparent swing of the resultant vector. In this latter case (frequency modulation) the maximum angle of swing would be inversely proportional to the audio frequency (as is indicated by equation 12). This is illustrated by figure 7 where the vectors for both frequency and phase modulation are drawn for two signals with an audio-frequency ratio of two to one. Note that in phase modulation the maximum angle ϕ_m is the same for both signals while for frequency modulation the maximum angle ϕ_m for signal A (the lower frequency) is twice that for signal B. Since the angular *velocity* is proportional to the instantaneous value of the signal in frequency modulation the vector reaches its maximum angle of deviation when the signal is zero while in phase modulation it reaches its maximum angle of deviation when the signal is a maximum.

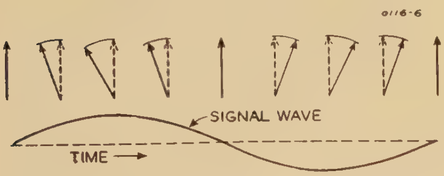


Figure 6. Vector diagrams of the angular-modulated wave of figure 4 for successive instants

Solid-line vectors are vectors of modulated wave

Dashed-line vectors are vectors of unmodulated wave

Other Types of Angular Modulation

Phase and frequency modulation are not the only possible types of angular modulation, but are only two members of an infinite group. Other possible types are:

(*c*). Angular Acceleration Modulation

In this type of modulation the second time derivative of ϕ is directly proportional to the signal function

$$\frac{d^2\phi}{dt^2}=b_3f(t)$$

In this type m_p would be inversely proportional to the square of the audio frequency.

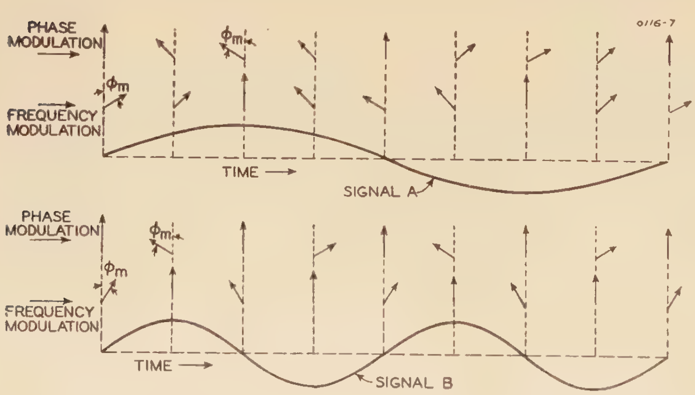
(*d*). nth Order Modulation

In this general type of angular modulation the *n*th derivative of ϕ is directly proportional to the signal function.

$$\frac{d^n\phi}{dt^n}=b_{n+1}f(t) \tag{13}$$

In this type m_p would be inversely proportional to the *n*th power of the frequency for modulating signals of equal intensity.

In radio transmission by angular modulation means are provided at the receiver so that the detected signal is proportional to the angular modulation (of the particular subdivision selected) and at the same time this detected signal is made unresponsive to amplitude variations. These means will be discussed in more detail later.



Note: ϕ_m is same for both signals for phase modulation. ϕ_m is inversely proportional to signal frequency for frequency modulation. Maximum velocities of vectors are same for both signals for frequency modulation

Figure 7. Comparison of phase and frequency modulation by means of vector diagrams

Interference of Two Angular-Modulated Waves

When two angular-modulated waves of the same carrier frequency are added together, the total angular modulation is not the sum of the two individual modulations. This is in distinct contrast to amplitude modulation where the resultant envelope is the sum of the individual envelopes.

This can be illustrated by figure 8 where an angular-modulated wave B is represented by a vector whose angle is changing with time. This is added to a larger vector A which for the moment will be assumed to be unmodulated. The resultant vector R will be the sum of the two vectors.

It is apparent that if B is less than A, then no matter what the total angular variation of B may be (even if it is hundreds of radians) the total angular variation between R and A cannot exceed $\tan^{-1}(B/A)$. For instance if $B/A=0.5$ the maximum value of m_p for the vector R when A is unmodulated is $m_p=0.46$. If $B/A=0.5$ and A in turn has its angle modulated, then the difference between the angle of A and that of R cannot exceed 0.46 radian at any instant. If the modulation factor (m_p) of A is made large in comparison with 0.46, the interference of B becomes negligible, in spite of the fact that the magnitude of B is by no means negligible in comparison with A.

This analysis justifies the experimental results which show that when two frequency-modulated signals are picked up by a receiver, there is no appreciable interference between the two signals if the stronger exceeds the weaker by a ratio of two to one or more.

It will be seen that the greater the value of m_p used for the desired signal the greater is the discrimination against the undesired signal, but this discrimination is not affected by the value of m_p used in the undesired signal.

The discrimination against interference obtained by angular modulation applies to all five types of interference enumerated in the early part of the paper. In particular static may be represented as a vector of varying phase and magnitude. The selective circuits of the receiver admit only those components within the band to which it is receptive. If the amplitude of the admitted noise does not exceed half the amplitude of the desired wave, a very small amount of noise will be introduced into the output. The greater

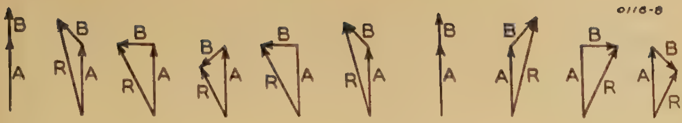


Figure 8. Vector diagrams showing interference in angular modulation

A is vector of desired signal—unmodulated
B is vector of interfering signal (same carrier)
R is vector of total wave $(A+B)$

the average phase deviation in comparison with the angle 0.46 (approximately 0.5) the greater will be the discrimination against the noise. It should also be observed that components of the noise vector which differ in frequency from the carrier by superaudible frequencies, will produce superimposed angular velocities above audibility and so do not contribute to the noise, as long as the noise is small compared with the signal.

In radio operation it will be found that if a portable receiver is driven in an automobile away from a frequency-modulated transmitting station, no appreciable noise will be experienced until the desired field strength drops to twice the noise field strength (taking into account only those components of noise accepted by the selective circuits of the receiver). The noise then rises rapidly, so that a sharp threshold is experienced.

Within the distance limited by the threshold, the signal-to-noise ratio can be improved by either increasing the power or increasing the modulation factor (either phase or frequency). Since power is proportional to the square of voltage or current in a given system, doubling the frequency deviation in frequency modulation has the same effect on the signal-to-noise ratio as increasing the transmitted power four times. In general an increase in the maximum frequency deviation by a ratio n would be equivalent in its effect on the signal-to-noise ratio to an increase in power by the ratio n^2.

The actual voltage produced by noise in the amplifier of a radio receiver increases with the width of the band accepted, the rate of increase depending on the type of noise. This introduces some disadvantage to the use of a wide band, because a stronger desired wave is necessary to insure that the desired voltage shall exceed the noise voltage.

R. F. Guy of the National Broadcasting Company reported before the Federal Communications Commission that in experiments with a one-kw transmitter and an antenna 1,000 feet high, the threshold for a value of m_f equal to 75 kilocycles was at 86 miles, while with an m_f of 15 kilocycles the threshold was at 100 miles due to the smaller noise voltage accepted by a more selective receiver. Within the threshold distances, however, there is a greater discrimination against noise with the greater frequency deviation.

The second major objection to the use of a large frequency deviation is that it would limit the number of stations which can serve a given area if a fixed total band width is allowed for the service.

A compromise must be reached and standard set before the use of frequency modulation is generally adopted so that the receivers may work with the transmitters. In order to study the possible

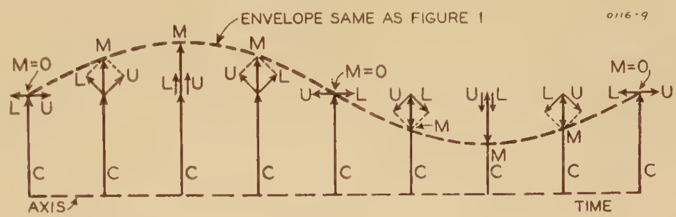


Figure 9. Vector diagram of carrier and side frequencies in an amplitude-modulated wave

C—Carrier vector (constant length)
U—Upper-side-frequency vector
L—Lower-side-frequency vector
M—Modulation vector (sum of *U* and *L*)
Vector of complete wave is sum of *C* and *M*

or required allotment, a spectrum analysis must be made of the different classes of modulation.

Spectrum Analysis of Amplitude Modulation

The wave of equation 2 may be expanded by the use of simple trigonometric identities. This equation becomes

$$e=A \sin \omega t+\frac{mA}{2} \cos (\omega-\rho)t-\frac{mA}{2} \cos (\omega+\rho)t \quad (14)$$

Equation 14 shows that the wave which is amplitude modulated by a single frequency may be analyzed into three component frequencies with the following designations:

$A \sin \omega t$	The carrier
$\frac{mA}{2} \cos (\omega-\beta)t$	The lower side frequency
$\frac{mA}{2} \cos (\omega+\rho)t$	The upper side frequency

The three components may be represented by three vectors rotating at different angular velocities. Again if the observer were rotating with the carrier vector, this vector would appear to be stationary. The upper side-frequency vector would appear to be rotating *counterclockwise* at a velocity ρ and the lower side frequency would appear to be rotating *clockwise* at the same velocity ρ.

The three vectors corresponding to the wave of figure 1 are shown in figure 9. It will be observed that the upper and lower side-band vectors add together to form a vector *M* called the modulation vector, which is always in phase with the carrier vector, but which varies in magnitude.

The three component frequencies of equation 6 are represented graphically in figure 10. This is shown primarily so that it may be compared later with the frequency spectrum used in frequency modulation.

If the original signal were a complicated sound wave instead of a single frequency, a spectrum analysis would show it to be represented by a band of frequencies. The lower and upper side frequencies would expand into two bands of frequencies each as wide as the band of the original audio signal. For instance if the signal were restricted to a band of 0–5,000 cycles the two side bands would extend from 5,000 cycles below to 5,000 cycles above the carrier frequency. Since the quality of a signal depends upon the width of the band which may be transmitted, an improvement in the quality of transmission would require an extension of the frequency spectrum occupied by the radio

Figure 10. Spectrum analysis of an amplitude-modulated wave

f_c—Carrier frequency
f_p—Audio frequency
A—Carrier amplitude
m_a—Modulation factor=0.5 in this case

wave. However, the narrower the frequency band which is used the greater will be the number of stations which can be accommodated. In practice a compromise must be made. Standard broadcasting stations in North America are assigned carrier frequencies in the range of 550 to 1,600 kilocycles, these assignments being separated at intervals of 10 kilocycles. In order to prevent interference, selective circuits are required in the receiver which are so sharp in most commercial models that side-band components more than 3,000 cycles away from the carrier are greatly attenuated. Hence the quality which is permissible in practical operation is limited by the major problem of interference.

Spectrum Analysis of Angular Modulation

The angular-modulated wave of equation 7 may be expanded by the use of the identities

$$\sin(p\sin x)=2[J_1(p)\sin x+J_3(p)\sin 3x+J_5(p)\sin 5x+\ldots] \quad (15a)$$

$$\cos(p\sin x)=J_0(p)+2[J_2(p)\cos 2x+J_4(p)\times\cos 4x+J_6(p)\cos 6x+\ldots] \quad (15b)$$

where $J_n(p)$ is the nth order Bessel function of the first kind. Equation 7 may be written

$$e=A[\sin\omega t\cos(m_p\sin\rho t)+\cos\omega t\times\sin(m_p\sin\rho t)] \quad (16)$$

If equations $15a$ and $15b$ are inserted in equation 16 the following result will be obtained

$$\begin{aligned}e=A\{&J_0(m_p)\sin\omega t+\\&J_1(m_p)[\sin(\omega+\rho)t-\sin(\omega-\rho)t]+\\&J_2(m_p)[\sin(\omega+2\rho)t+\sin(\omega-2\rho)t]+\\&J_3(m_p)[\sin(\omega+3\rho)t-\sin(\omega-3\rho)t]+\\&J_4(m_p)[\sin(\omega+4\rho)t+\sin(\omega-4\rho)t]+\\&\ldots\ldots\ldots\ldots\ldots\ldots+\\&J_n(m_p)[\sin(\omega+n\rho)t+\\&(-1)^n\sin(\omega-n\rho)t]\}+\\&\ldots\ldots\ldots\ldots\ldots\ldots\end{aligned} \quad (17)$$

This indicates that there are an infinite number of side frequencies for a single-frequency signal. However this is not as bad as might at first appear because for any given value of m_p, there will be a value of n above which the coefficients $J_n(m_p)$ fall off rapidly and become negligible. This is shown in figure 11. For example if m_p is one-half radian or less, only the first pair of side frequencies is important. On the other hand if m_p is equal to 20 radians, side frequencies out to the 24th pair would be appreciable. For large values of n this rapid falling off of $J_n(m_p)$ occurs just beyond $n = m_p$. Observe also that the value of the carrier component is always reduced when modulation occurs since $J_0(m_p)$ is less than one for all values of m_p different from zero. This is in contrast with amplitude modulation where the value of the carrier is not affected by modulation.

Figure 4 was drawn for a phase-modulation factor of 0.5 and so the first pair of side bands are the only ones of importance. If all other side bands are neglected the vector diagrams including the side

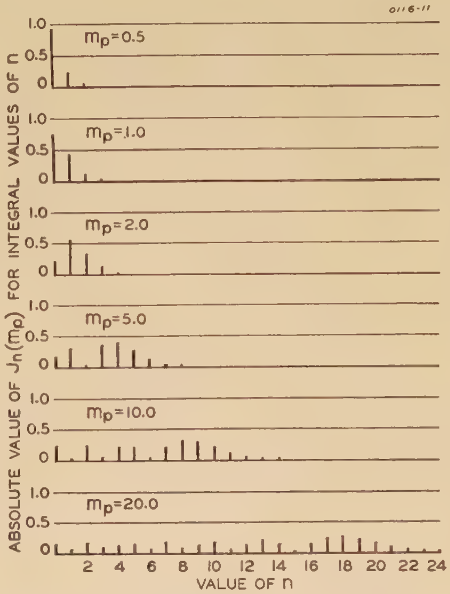


Figure 11. Values of the Bessel function of the first kind for integral orders

bands for different instants of figure 4 can be shown as in figure 12. The signal wave is shown for identification. The carrier and resultant vectors are the same as those shown in figure 6. The modulation vector, which is the sum of the two side-band vectors, is always 90 degrees out of phase with the carrier and varies in magnitude in the same way that the modulation vector varies in amplitude modulation. The neglect of higher-order side frequencies is the same as an assumption that there is a negligible difference between the arc and a tangent line of the same length when the angle is small.

When the modulation vector is added to the carrier vector it causes the resultant vector alternately to advance beyond and retard behind the carrier vector. The maximum advance and retardation is approximately one-half radian. The length of the resultant vector is substantially constant. If the additional side bands were included the length of R would be exactly constant.

If the phase modulation exceeds one-half a radian additional side bands must be included because the arc and chord are no longer substantially the same. The addition of the vectors corresponding to these side bands is illustrated in figure 13 for $m_p=1$ and for one-quarter of an audio cycle, the other three-quarters being similar. It will be noticed that each pair of side bands has associated with it a modulation vector which maintains a constant phase with respect to carrier (assuming that phase reversals are taken care of by negative signs).

If the modulated wave represents a quantity whose square is proportional to power in a given system the *average* power in an angular-modulated wave is not changed by the modulation, as the rms value of the wave is not modified if the amplitude remains constant. Therefore the square root of the sum of the squares of the carrier and all the side-band components remains constant for all values of m_p. The side-band power is obtained by a reduction in carrier power. This is also proved by the well-known relation

$$J_0^2(m_p)+2\sum_{n=1}^{n=\infty}J_n^2(m_p)=1$$

for all values of m_p. The number of terms which are of importance in the infinite series can be evaluated by setting

$$J_0^2(x)+2\sum_{n=1}^{n=s}J_n^2(m_p)\geq\lambda$$

Then if λ is taken as some value less than unity, the sum can terminate with a finite value of n equal to s. If λ is equal to 0.999 then 99.9 per cent of the energy in the wave would be due to side-band components corresponding to values of n equal to or less than s.

For example, if $m_p = 4$ and six components are taken in each side band

$$\begin{aligned}J_0^2(m_p)+2\sum_{n=1}^{n=6}J_n^2(m_p)&=0.157688+\\&2(0.004356+0.132569+0.185072+\\&0.079017+0.017450+0.002411)\\&=0.999438\end{aligned}$$

and all the components corresponding to $n>6$ would contain only 0.0562 per cent of the energy.

The constancy of power output is in marked contrast to amplitude modulation where the carrier power remains constant and the side-band power is added. For that reason certain problems in design are simplified in a phase- or frequency-modulated transmitter. This will be discussed in the section on transmitters.

Comparison of the Spectra of Phase and Frequency Modulation

In phase modulation the value of m_p is made directly proportional to the maxi-

Table I

Audio Frequency	m_p for 60,000-Cycle Deviation	Approximate Number of Side-Band Components Required	Approximate Band Width in Kilocycles
30	2,000	4,030	120.06
60	1,000	2,020	120.20
600	100	208	124.8
2,500	24	46	140
3,000	20	24	144
5,000	12	30	150
10,000	6	16	160
15,000	4	12	180

mum value of the signal. If two different audio frequencies have equal amplitudes, and modulate the signal in succession, the same number of side-band components would be necessary for each case and these components would have the same relative magnitude. It has been shown that the advantage of angular modulation in the reduction of interference requires the use of large values of m_p for the desired signal. If the value of m_p for a special case is taken equal to 20, then by figure 11 it is apparent that approximately 24 side-band components would be desirable for the upper side band and a similar number for the lower side band. Therefore if an audio signal of high quality containing components up to 15,000 cycles were to be transmitted, a band width of approximately $2\times24\times15{,}000$ or 720,000 cycles would be required. This is obviously impracticable. For this reason phase modulation (as distinguished from frequency modulation) has not been used for radio transmission.

In frequency modulation the value of m_f is made directly proportional to the maximum value of the signal. If two different audio frequencies have equal amplitudes and modulate the signal in succession with equal values of m_f, by equation 12 the values of m_p for the two cases will be inversely proportional to the audio frequency. Thus if m_p is equal to 4 for 15,000 cycles it would be equal to 40 for 1,500 cycles and equal to 400 for 150 cycles. A study of figure 11 shows that the number of components of appreciable magnitude in each side band is slightly in excess of m_p. Therefore as the modulating frequency is reduced, the number of components necessary increases, and the modulated wave occupies almost a constant band width in the spectrum. As an example consider a case where the maximum frequency deviation is assumed to be 60,000 cycles. Then if a high quality signal is to be transmitted, frequency components in this signal up to 15,000 cycles might be desired. If the wave were frequency modulated with a 60,000 cycle deviation ($m_f=60{,}000$) at 15,000 cycles m_p would equal $60{,}000/15{,}000=4$ radians. For this case figure 11 shows that approximately six components in each side band separated at intervals of 15,000 cycles are desirable and the corresponding band width would be $2\times6\times15{,}000$ or 180,000 cycles. On the other hand if the wave were to be frequency modulated with a 60,000 cycle deviation by a 3,000 cycle wave $m_p=60{,}000/3{,}000=20$ and approximately 24 components in each side band separated at intervals of 3,000 cycles would be desirable. The band width for this signal would be $2\times24\times3{,}000=144{,}000$ cycles which is somewhat less than that needed for $m_p=4$ at 15,000 cycles. Table I is constructed for a maximum deviation of 60,000 cycles.

The spectrum analysis for a deviation of 60 kilocycles and modulating frequencies of 2,500, 5,000, 10,000, and 15,000 cycles is shown in figure 14 and it is apparent that the signal is contained within a band width of approximately 200 kilocycles in all cases. In practice, no audio signal would contain only the higher audio frequencies and so it is found practicable to use a deviation of m_f of 75,000 cycles for a band width of 200 kilocycles.

The spectrum analyses for a modulating frequency of 15,000 cycles and deviation frequencies of 30, 15, 7.5, and 3.0 kilocycles are shown in figure 15.

It is apparent from figures 14 and 15 that when the deviation frequency is large compared with the audio frequency, the band width required is approximately twice the deviation frequency while when the audio frequency is large compared with the deviation frequency the band width is twice the audio frequency. The latter case coincides with the situation in amplitude modulation. In other words the band width required is approximately twice the larger of the two frequencies (audio or deviation). If the audio and deviation frequencies are approximately equal the band width required is approximately four times that of the larger frequency. (See figure 15 for $m_p=0.5$, 1, and 2.)

The spectra of figures 14 and 15 may be used for any other combinations of audio and deviation frequencies which have the same deviation ratio m_p by modifying the scale of abscissa so that the interval between adjacent components is equal to the audio frequency.

The reader must be cautioned that if a signal contains two or more audio frequencies, the resultant spectra cannot be obtained by adding the spectra resulting from each audio frequency alone (as can be done in amplitude modulation). However, the total spectra will remain approximately within the limits set by the maximum frequency deviation when the latter is large.

Although the discrimination against noise is proportional to m_p, it is impracticable to use large values of m_p at all audio frequencies because of the band width involved. However, noise and interference is the composite result of a larger number of noise components. If frequency modulation is employed, the maximum value of m_p is obtained for each audio component in the signal which will at the same time keep the side-band components within the limits in the spectrum assigned to the transmission. Therefore frequency modulation is the type of angular modulation which reduces the composite noise effect to the greatest practicable extent.

If the maximum modulation factor m_p (deviation ratio) is low, m_p less than 0.5, frequency modulation does not appear to have any advantages over amplitude modulation. The early proposals for the use of frequency modulation envisioned this method of operation and so were dis-

C—Carrier vector
U—Upper-side-frequency vector }
L—Lower-side-frequency vector } First pair only
M—Modulation vector (U+L) }
R—Resultant vector (C+M)

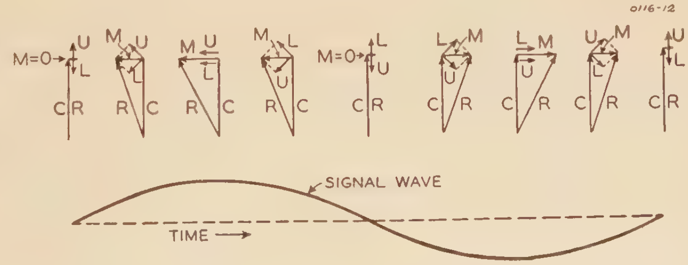


Figure 12. Vector diagram of carrier and side frequencies in an angular-modulated wave for low values of modulation

carded after the analyses of Carson[1] and Roder.[2]

Practical Considerations in Frequency Modulation

It has been shown that the reduction of interference makes frequency-modulated transmitters most desirable for the transmission of high-quality signals. However these transmitters require relatively large frequency bands. Therefore frequency modulation, or F-M, does not appear to be feasible in the present broadcast band. For high-quality broadcasting they should be allocated to high frequencies where band widths of 200 kilocycles are available. The Federal Communications Commission has assigned the frequencies from 42 to 50 megacycles for this service or a total of 40 channels. This is in the range of the so-called ultrahigh frequencies.

Radio waves with frequencies of the order of 40 megacycles and above are not reflected from the ionosphere, and so their range is limited by the curvature of the earth. For the same reason static is greatly reduced at these frequencies because the energy which lies in the ultrahigh-frequency spectrum and which is originated by electrical disturbances at distant points on the earth's surface cannot travel to the receiver over long distances. Other factors also reduce static at high frequencies. As an average, the static voltage producing interference in a receiver with a given band width and tuned to 40 megacycles is about $^1/_{40}$ of the static voltage which would be picked up by a receiver of the same band width tuned to 1,000 kilocycles. It is also possible to transmit a wide-band audio signal which requires corresponding wide side bands at ultrahigh frequencies because for practical reasons it is not desirable to assign carrier frequencies as close together as in the standard broadcast band and so sufficient band width is available for high-quality transmission. Therefore ultrahigh frequencies inherently offer an improvement in quality whether amplitude or frequency modulation is used.

However, there are three important difficulties with ultrahigh-frequency transmission for broadcasting purposes. The first difficulty is the effect of the curvature of the earth on ultrahigh frequencies. Because there is no reflection from the ionosphere, it is frequently stated that the limit of transmission for these frequencies is the distance from the transmitting antenna to the horizon. The equation for this distance is

$$d = 1.22\sqrt{H} \qquad (18)$$

where

d is the distance to the horizon in miles
H is the height of the transmitting antenna in feet

For a height of 400 feet the distance to the horizon would be only 24.4 miles.

Within this distance the field strength of the signal is given approximately by the equation[6]

$$E = \frac{0.0105\sqrt{WGHAF}}{D^2} \qquad (19)$$

where

E = field strength in microvolts per meter
W = power in watts
G = gain of the antenna over a half-wave dipole
A = receiver antenna height in feet
F = frequency in megacycles
D = distance in miles

The formula and the statement that the transmission is limited to the horizon are not strictly true because it is found that diffraction and refraction of the waves produce a signal[7] beyond the horizon, but this signal falls off more rapidly than the inverse-distance-squared term of equation 19.

The second difficulty with ultrahigh-frequency transmission is the noise produced locally by electrical apparatus. The principal sources of this noise are automobile ignition and fever therapy machines. These sources might be eliminated in time by legislation requiring adequate shielding.

A third difficulty with ultrahigh-frequency transmission is the sharp shadows thrown by buildings, hills, etc. Sharp shadows are produced in the field of any wave motion when the interfering bodies have dimensions large in comparison with the wave length, and so are particularly apparent at ultrahigh frequencies (short wave lengths).

Because of these difficulties the transmission of amplitude-modulated waves at ultrahigh frequencies has not made very much progress for broadcast transmission. However, these difficulties are only aspects of the fundamental problem pointed out at the beginning of the paper, that radio transmission is limited by the ratio of interference to signal. It has been shown that frequency modulation offers an important improvement in the solution of this problem. By its means the signal-to-noise ratio at any fixed distance may be increased. It seems probable an increase in transmission range may be secured by frequency modulation due to the greater signal-to-noise ratio and this may make economically feasible the use of ultrahigh frequencies for broadcasting purposes.

In field tests, adequate signals for the operation of an F-M receiver at two to three times the horizon distance are regularly reported when the transmitter is a high-powered one.

The wide band width which is required for frequency modulation is compensated

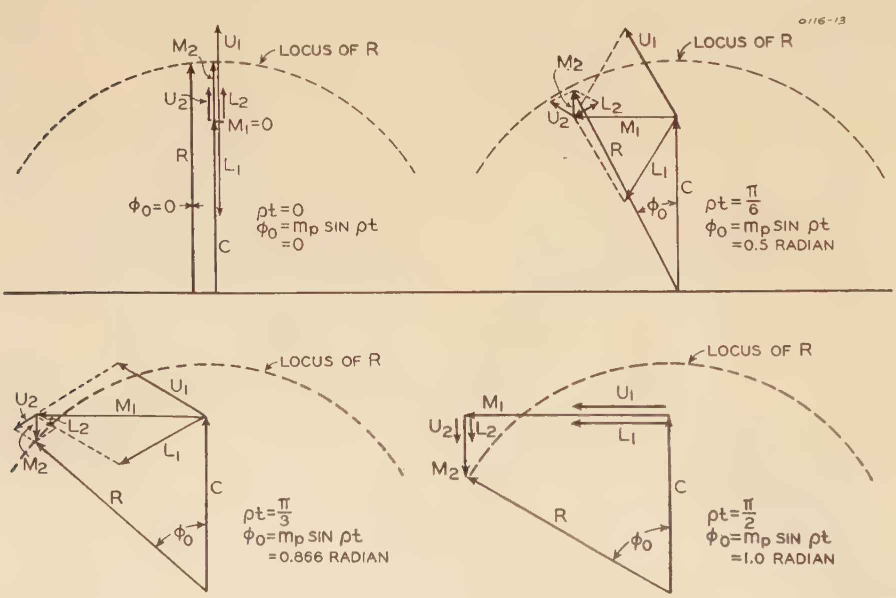
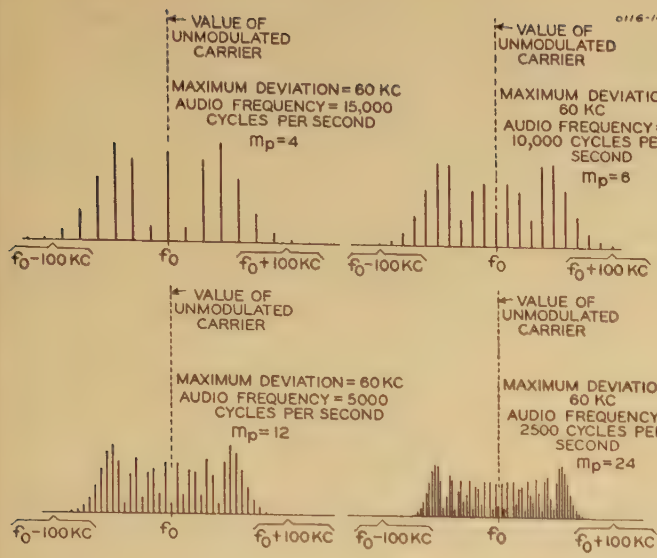


Figure 13. Vector diagram of carrier and two pairs of side frequencies in an angular-modulated wave where $m_p = 1$

U_1—First upper side band vector
L_1—First lower-side-band vector
M_1—First modulation vector (U_1+L_1)
U_2—Second upper-side-band vector
L_2—Second lower-side-band vector
M_2—Second modulation vector (U_2+L_2)
C—Carrier vector
R—Resultant vector



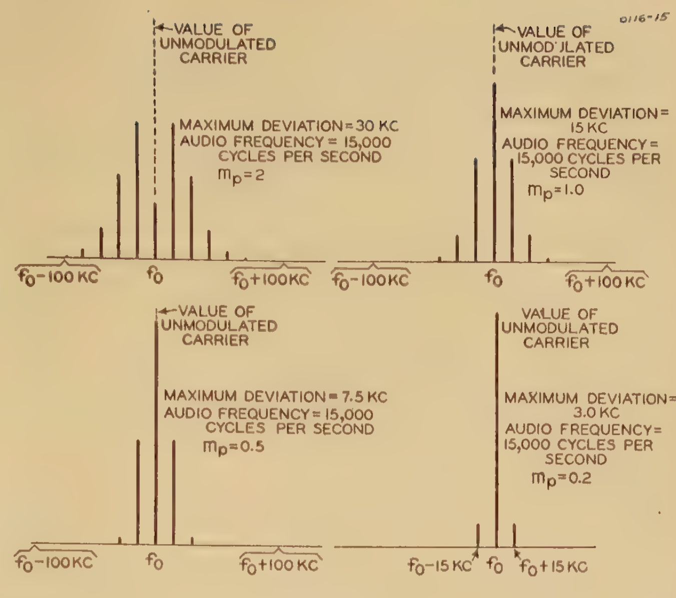


Figure 14 (left). Spectrum analysis of frequency modulation for a constant deviation and variable modulating frequencies

Figure 15. Spectrum analysis of frequency modulation for a constant modulation frequency and variable deviation frequency. (Signal is for phase modulation)

for by the reduction in interference between two stations on the same channel. In amplitude modulation, interference is caused if an undesired signal is one per cent of the desired signal. It has been shown that in F-M a ratio of two to one between desired and undesired signals is sufficient. If two stations of equal power and located in neighboring cities should operate on the same channel, there would be only a small territory about half way between the two stations where there would be any interference. Even in this territory, relatively simple directional antennas would be sufficient to pick out one station or the other. Therefore numerous stations could be located throughout the nation on the same carrier frequencies.

I. R. Weir, of the General Electric Company reported before the Federal Communications Commission that in their experiments they used a 150-watt transmitter at Albany and a 50-watt transmitter at Schenectady, a distance of 14.5 miles. They operated both transmitters on the same frequency with both frequency and amplitude modulation. In driving a car equipped with a receiver along a line between the two stations the following results were obtained:

Type of Modulation	Interference-Free Range of Albany Station	Transitional Distance With Interference	Interference-Free Range of Schenectady Station
Frequency	10.5	1.0	3.0
Amplitude	3.3	11.7	0.5

A further advantage of frequency modulation in the operation of the transmitter and receiver is that nonlinear distortion in frequency modulation is not affected by the nonlinearity of the tubes, as their nonlinearity is a function of amplitude. In F-M nonlinear distortion depends only on circuit design, that is, on nonlinear relations which are a function of frequency. For that reason it is claimed that high-quality reproduction is more practicable.

Frequency-Modulation Receivers

In the discussion of F-M receivers and transmitters, a certain familiarity with communication theory must be assumed in order to conserve space. The discussion will deal with present commercial practice.

Frequency-modulated receivers differ from amplitude-modulation receivers in three important respects. They are:

(*a*). The inclusion of a *limiter* to remove any amplitude modulation resulting from an interfering signal.

(*b*). The use of a special detector circuit called the discriminator to change the frequency modulation into a variable-amplitude signal.

(*c*). The use of a wide-band intermediate amplifier.

In addition it is much more important in a frequency-modulation receiver to have a high-gain intermediate-frequency amplifier, because the operation of the limiter is dependent upon a certain minimum signal being applied to its input. Also, if advantage is to be taken of the high-quality transmission which is possible with F-M, a better-than-average audio system and loud speaker should be included.

Except for these differences, the F-M receiver will follow the practice of amplitude-modulated receivers. The use of superheterodyne receivers is universal.

If a tuned-radio-frequency amplifier has impressed upon its grid a high-frequency voltage exceeding a certain minimum amplitude, the radio-frequency current in the tuned plate circuit will be practically independent of the magnitude of the input. This is because after the radio-frequency component of voltage in the plate circuit has reached an amplitude equal to the d-c component of the plate voltage no further increase in the radio-frequency component can be obtained for the instantaneous value of plate voltage cannot be driven negative. By the use of a high-gain tube and low values of plate voltage, saturation at relatively low values of grid excitation may be obtained. Figure 16 shows the circuit and the limiting action for a typical commercial F-M receiver. The operation of the limiter is the same as that of a class *C* amplifier[5] and the use of a bias obtained by a resistance in the grid circuit assists in securing a flat curve.

The use of a limiter is necessary because any amplitude modulation which reaches the detector will also produce amplitude variations in the reproduced signal. *The use of the limiter or its equivalent at the receiver is the most important component in an F-M system, for no reduction in interference will occur without its operation.* The limiter is possible in frequency modulation because the saturation does not affect the instantaneous frequency of the output.

The elimination of hum due to the use

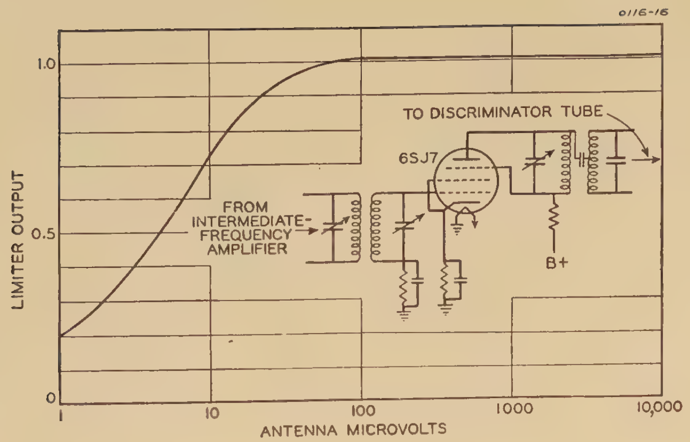


Figure 16. Characteristic and circuit of a limiter

of a-c supplies in receivers has also been a problem for many years. The principal source of this hum is amplitude modulation produced in the receiver by the hum component of the rectified d-c plate supply and by the heating of the cathodes by alternating current. If this occurs in the early stages of the receiver it is amplified along with the signal. While this hum level is reasonably well controlled in modern receivers, the limiter in a frequency-modulated receiver provides an additional improvement. This is particularly important because the elimination of other sources of interference makes the reduction of hum to an extremely low level much more desirable.

Because the audio amplifier and loudspeaker must reproduce the amplitude variations of the original signal, the discriminator or detector circuit must change the frequency variations into amplitude variations. The most common discriminator circuit in use is that of figure 17. The tuned transformer L_1-L_2 has a split secondary feeding two diode plates with the resistance loads R_1 and R_2. The voltage E_3 will be 90 degrees out of phase with the voltage across L_2 at the resonant frequency of L_2-C_2. The radio frequency across diode 1 in series with resistance R_1 is represented by the vector $E_a=E_1+E_3$ while that across diode 2 in series with resistance R_2 is $E_b=E_2+E_3$. When the output of the discriminator is at the intermediate frequency the phase relations will be those shown in diagram *A*. However, when the frequency shifts, the voltage across L_2, (E_1-E_2), shifts in phase. It can be shown that this voltage will follow the locus indicated by the circles. Hence E_a and E_b change in magnitude, one decreasing and the other increasing. By detector theory[5] the instantaneous value of the voltage across R_1 is proportional to E_a while that across R_2 is proportional to E_b. Therefore the instantaneous voltage E_4 supplied to the audio amplifier changes. Increases in frequency make E_4 positive and decreases make it negative.

The relation between the frequency deviation and the instantaneous value of E_4 is also shown in figure 17 for a typical receiver. The circuit constants must be selected so that the straight-line portion of the characteristic will accommodate the frequency shift which is used at the transmitter. The linearity of this characteristic affects the nonlinear distortion in the reproduced signal. It should be observed that its linearity is not a function of the tube characteristic. This makes it apparent that it is necessary to adopt standards at both receiver and transmitter which will be co-ordinated.

After a hearing before the Federal Communications Commission where all the problems were thoroughly discussed, the band width of 200 kilocycles per channel was adopted as standard. The allocation of channels adjacent to each other in the range of 42 to 50 megacycles simplifies the problem of receiver design, since no band-switching equipment will be required.

Because the intermediate amplifier must amplify a wider band of frequencies than is necessary in amplitude modulation a higher intermediate frequency is used. The present standard adopted is 4.3 megacycles for the intermediate carrier frequency.

A system which uses negative-frequency feedback in the receiver[8] has been proposed. It accomplishes similar results to those obtained by the use of the limiter, but as it is not at present available commercially, it will not be discussed here, although additional advantages are claimed for it.

Receivers are being manufactured which receive both amplitude and frequency modulation. In these combined receivers separate intermediate frequency transformers and detectors must be used. This makes the combination receiver somewhat more complicated, but complicated circuits have never been a bar to commercial production. This is exemplified by superheterodyne receivers retailing for $10 which have more extensive circuits than $200 sets of 15 years ago.

Frequency-Modulation Transmitters

Two important and quite different methods of obtaining frequency modulation are in use at the present time. A third method has also been announced.

The method proposed by Armstrong[3] makes use of the fact that for low values of m_p (m_p less than 0.5) the fundamental difference between amplitude and phase modulation lies in the phase relation between the carrier and side-band vectors. This is illustrated by a comparison of figures 9 and 12. Balanced modulators have been extensively used[5] in carrier-current systems to obtain the two side bands of amplitude modulation and eliminate the carrier. In the Armstrong system the carrier output of the oscillator is shifted 90 degrees and then used in a balanced modulator to obtain side-band components corresponding to amplitude modulation with this carrier phase. The output is then added back to a carrier component with the phase of the oscillator to form a phase modulation system. The maximum allowable modulation factor m_p produced with these components is 0.5 since only one pair of side frequencies is available.

A block diagram showing the Armstrong system is shown in figure 18. The

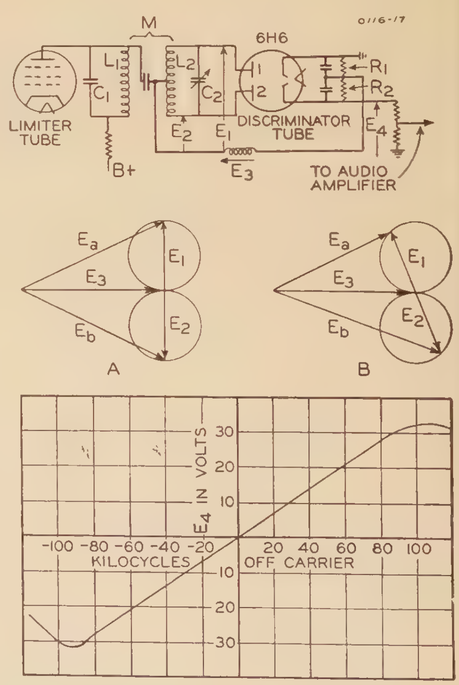


Figure 17. Characteristics and circuit of a frequency discriminator

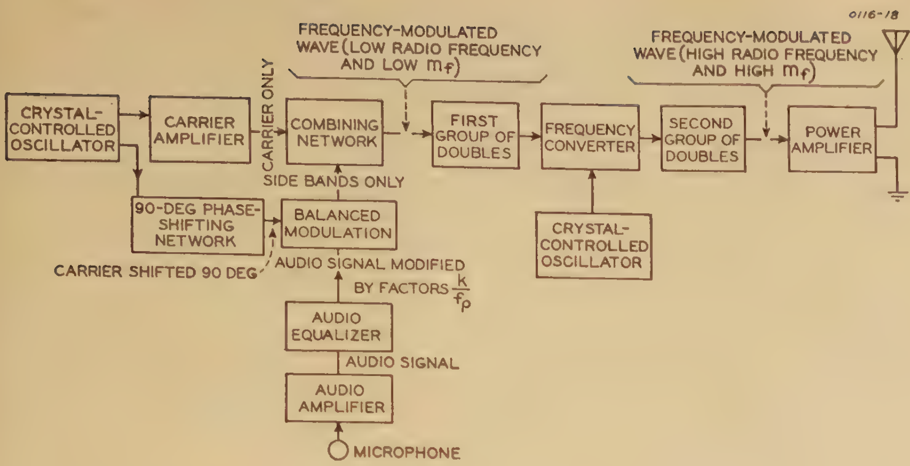


Figure 18. Block diagram of Armstrong frequency-modulated transmitter

several components required will be discussed in turn.

This method is fundamentally a phase-modulation system, but it may be converted into a frequency-modulation system if an audio equalizer is used before the modulation. The required characteristic of this equalizer is that the output voltage must be inversely proportional to the audio frequency of the input voltage. With this equalizer in the audio system the phase modulation will be inversely proportional to the audio frequency of the original signal. It has been shown that this is the requirement for frequency modulation and so the combination produces true frequency modulation.

It has been explained that with this system m_p is limited to a maximum value of 0.5, in the original modulation. On account of the characteristic of F-M which has been discussed, this maximum value of m_p can only be secured at the lowest audio frequency to be transmitted. The value of m_p at higher frequencies will be inversely proportional to the audio frequency. Then if a range from 40 to 15,000 cycles is to be transmitted the maximum value of m_p at 15,000 cycles will be $40/15{,}000 \times 0.5 = 0.0013$.

Such a method of obtaining frequency modulation, if used alone, would be entirely impractical since operation would be restricted to such low values of m_p and the advantages of frequency modulation lie in the use of large values.

If a radio-frequency amplifier has a large grid bias and relatively large radio-frequency voltage applied to its grid, the plate current will flow in pulses[5] containing harmonics of the grid exciting voltage. If the plate circuit is tuned to a harmonic of the grid voltage, the voltage across the tuned circuit will have a high value at this harmonic. For efficient operation this harmonic should be a low one, say the second or third. When tuned to a second harmonic the combination is called a frequency doubler.

It has been found that a frequency doubler also doubles the phase or frequency shift if an angular modulated wave is applied to the grid, and therefore doubles the value of m_p and also m_f for such a wave. A series of n doublers would multiply m_p by 2^n.

If the method of obtaining frequency modulation now being discussed is operated with a relatively low carrier frequency and the output is passed through a sequence of doublers or triplers, the value of m_p can be correspondingly increased. It has been shown that if a deviation of 75,000 cycles is desired, the value of m_p at an audio frequency of 15,000 cycles would be $75{,}000/15{,}000 = 5$. It has also been shown that for the wide audio range of 40–15,000 cycles the n_p which can be initially produced by the Armstrong method at an audio frequency of 15,000 cycles is 0.0013. Therefore the amount of multiplication of m_p required is approximately $5/.0013 = 3{,}750$. The number of doublers required is then obtained by the solution of the equation

$$2^n = 3{,}750$$

or

$$n = 12 \text{ nearly}$$

If a final carrier frequency of 41 megacycles is to be used and straight multiplication were to be employed, the carrier frequency at which the initial modulation should take place would be determined by the frequency multiplication required. In this case

$$\text{Initial carrier frequency} = \frac{\text{Final carrier frequency}}{\text{Multiplication of doublers}} = \frac{41{,}000{,}000}{2^{12}} = 10{,}000 \text{ cycles per second}$$

It is not possible to modulate a 10,000-cycle carrier by an audio frequency of 15,000 cycles, since the audio frequency must be less than the carrier frequency. Therefore some modification of the system must be made. The modification adopted is to perform the modulation at an initial carrier frequency of the order of 200 kilocycles and pass it through a first group of say six doublers. The carrier frequency has then been multiplied 2^6 times and has reached a value of 12.8 megacycles. If now a final carrier frequency of 41 megacycles is desired, the 12.8 megacycle signal is combined with the output of a second crystal oscillator whose frequency is selected so that a beat note of $41/2^6$ or 0.6406 megacycle is obtained. This does not affect m_p. The 640.6-kilocycle wave is then passed through a second group of six doublers to obtain the final 41-megacycle output. Since the initial frequency-modulated wave has now passed through 12 doublers, the multiplication of 2^{12} or 4,096 has been obtained.

The output of the second group of doublers is then amplified up to the final power required.

While this circuit seems complicated, it should be remembered that these operations can be performed at low power and with receiving-type tubes. The cost is not prohibitive for a transmitter station, since the investment in other equipment would be much greater.

The second method of frequency modulation operates in a distinctly different manner. If the capacity of a capacitor could be varied at an audio rate, and if this capacitor were included in the tuned circuit of an oscillator, it is apparent that the output would be frequency modulated.

The fundamental characteristic of a re-

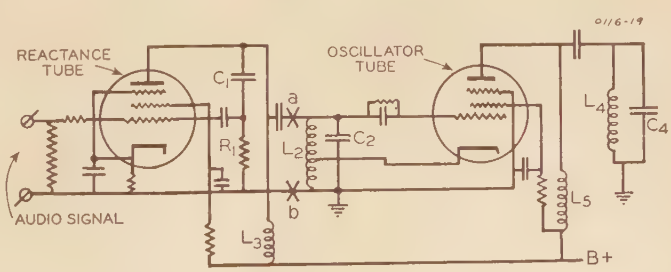


Figure 19. Circuit of an oscillator which is frequency-modulated by a reactance tube

actance is that the current flowing into the two terminals is 90 degrees out of phase with the voltage applied across these terminals. This same effect can be secured with a tube circuit. The method is illustrated in figure 19. The resistance R_1 is made small in comparison with the reactance of C_1. Then the alternating voltage between the control grid and cathode is substantially 90 degrees out of phase with the voltage impressed across the terminals *a-b*. But the plate current which flows in the tube is determined largely by the grid voltage. The choke L_3 provides a large impedance to alternating current so that the a-c component of the plate current will flow in the terminals *a-b*. The current which flows into the terminals *a-b* will be 90 degrees out of phase with the voltage across it because of the grid control and the circuit appears like a reactance at these terminals.

The magnitude of the reactance is a function of the amplification constant of the tube. In a variable-mu tube the amplification constant may be controlled by the voltage on the grid. Therefore if an audio voltage is also impressed on the control grid of the tube the effective reactance may be varied at an audio rate.

The terminals *a-b* are connected in parallel with the tuned circuit L_2-C_2 of a conventional oscillator whose output frequency is determined by the resonance of that circuit. With this combination a variation in the audio voltage on the grid of the reactance tube will produce a frequency-modulated wave in the output circuit of the oscillator L_4-C_4.

The circuit of figure 19 does not have the inherent stability of the system of figure 18 because the carrier frequency or frequency for zero modulation is not crystal controlled. Stability equivalent to crystal control is necessary in modern radio operation. In order to secure crystal control a more elaborate system is necessary. This is illustrated by the block diagram of figure 20.

The oscillator and reactance circuit are similar to those of figure 19. The oscillator usually operates at some submultiple of the desired frequency, say one-fourth or one-sixth. A frequency multiplier is used before the operation of the final power amplifier, as is standard practice at ultrahigh frequencies. A sample of the output is brought back into a frequency converter where it is mixed with the output of a crystal oscillator for comparison purposes. The resultant beat note is then passed through a frequency discriminator of the same general type as used in receivers and illustrated in figure 17. If the final output changes frequency, the beat frequency passing into the discriminator will change. This change is used to produce a direct voltage in the discriminator which in turn is applied to the reactance tube to provide a correction on the frequency drift which has occurred.

This method of increasing stability has a marked similarity to the use of inverse feedback in audio amplifiers to increase their stability.

A delay or filter must be introduced in the frequency feedback circuit so that it is unresponsive to the variations in frequency produced by the audio modulation, but will make corrections for the long period drifts associated with oscillators which are not crystal controlled.

The two methods of frequency modulation transmitters each have their proponents. The Armstrong method is claimed to be more stable because the carrier frequency is directly controlled by the two crystals. The reactance tube method is simpler and would seem particularly applicable to low powers and portable equipment. It is too soon in terms of practical operation to be sure which will find the most general application.

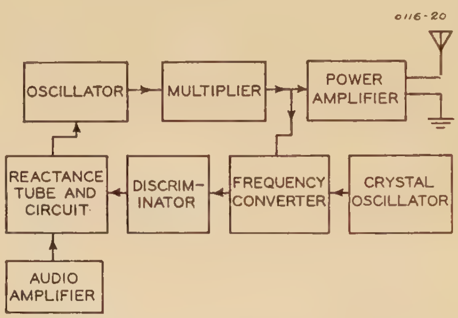


Figure 20. Block diagram of a reactance-tube-controlled frequency-modulated transmitter with crystal stabilization

The operation of the final amplifiers in both systems is essentially simpler than is the case in amplitude modulation, since attention need not be paid to the linearity of input-output amplitude curves.

In amplitude modulation the final high-power stage presents certain difficulties in operation. A transmitter normally requires[5] either a high-power audio amplifier with an output about 75 per cent of the rated carrier power to perform the modulation, or else the final stage must be operated at half its maximum efficiency. This is because in amplitude modulation the power output must be increased during modulation by an amount equal to the side-band power (50 per cent of the carrier power for $m=1.0$). The increase in power must be supplied by either an audio amplifier or by an increase in the efficiency of the output stage during the audio cycle. An increase in efficiency can only be obtained if the efficiency in the absence of modulation is limited to half its maximum possible value. Both of these expedients increase the cost of high-power stations materially. Since the amplitude and power output of an F-M transmitter are constant during modulation, the final stage can operate at its maximum efficiency at all times even though the original modulation is performed at a low power level where only receiving-type tubes are required.

The question is frequently raised whether the wide band which must be transmitted for F-M does not introduce difficulties in the tuned circuits. However, it should be remembered that the selectivity of any tuned circuits is given in terms of frequency ratio rather than absolute band width. A 200-kilocycle band width at 40 megacycles is only one-half of one per cent of the carrier frequency, while the 10-kilocycle band width used in standard broadcasting at 1,000 kilocycles is one per cent of the carrier frequency. Therefore no difficulties are introduced in the transmitter by the required absolute width of the band when the carrier frequency is high.

Application of Frequency Modulation to Services Other Than Broadcasting

Frequency modulation seems to have inherent advantages for other services than broadcasting. Important among these are its application to police and airway communication. The sharp limitation of the range obtained with F-M is an advantage and it would appear that many more police transmitters covering specific areas could be used without interference. In airway service some of the most important contacts are needed during severe electrical storms and F-M could make an important contribution in this field.

F-M would also appear to have advantages for military purposes where limited ranges are desired and interference is a particularly severe problem.

In police, airway, and military communication, high-quality reproduction is not necessary and so a more limited band would serve the purpose.

F-M has also been proposed for longer-distance communication by the use of relay or repeater stations spaced at intervals determined by the range of the transmitters. By the use of directional antennas this range can be increased. Previous proposals to use relay stations for

broadcast-station interconnection have not met with favor because of the limited range and additional interference which they would cause, but it appears that a large part of this objection is eliminated when F-M is used.

It is also possible to multiplex other services on F-M transmission, such as facsimile, transmitting this service along with a sound signal, but with a reduction in the signal-to-noise ratio. Another suggestion has been to transmit two sound signals to obtain binaural reproduction. The possibilities of these uses have been only partially explored.

Conclusion

It would appear that frequency modulation is capable of producing a marked change in broadcasting within the next few years. It is very doubtful if it will eliminate the use of the standard broadcast frequencies, as they are still capable of covering larger distances when (and only when) a transmitter is given exclusive use of a channel. It seems probable that many local stations designed to cover a limited area will be transferred to F-M operation, and the number of cleared channels increased so as to take better advantage of the limited band of standard broadcast frequencies available. The development in these lines must eventually respond to the laws of economics and engineering.

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Low-Voltage D-C Measurements on Electrical Insulating Oils

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THE development work and experimental results presented herein have been a part of a co-operative project of the Utilities Co-ordinated Research, Inc. (Association of Edison Illuminating Companies) and the Massachusetts Institute of Technology. The purpose of this joint research project is the investigation of the mechanism of the deterioration of electrical insulating oils and the development of methods and apparatus for the study of this deterioration, with special reference to its influence on the electrical characteristics. It was for this reason that it was desirable to investigate the conductance of electrical insulating oils and methods of determining the conductance of such oils.

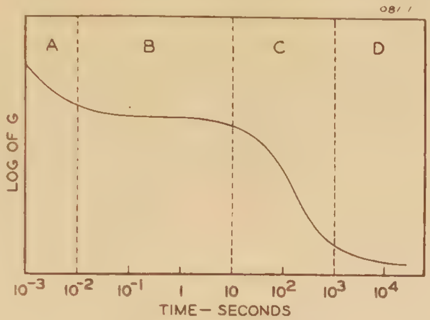

Figure 1. Variation of conductance with time at high gradients

General Considerations

In the usual conductance test for electrical insulating oils[1] the conductance is measured by means of a galvanometer used as an ammeter. A cell with a guarded electrode is used and from 500 to 1,500 volts potential difference is applied across the cell giving a potential gradient of from 200 to 1,200 volts per millimeter. The conductance (or resistance) is computed from the current reading one minute after the voltage is applied. As has been shown, principally by Whitehead,[2] this value is entirely empirical and often does not represent either the initial or the final conductivity of the oil. Using an amplifier-oscillograph and potential gradients of 500, 1,000, and 1,500 volts per millimeter Whitehead was able to measure the change of conductance with time from about 0.001 second after the application of voltage. The general type of the curve thus obtained for oils of low conductance is shown in figure 1.

Region *A* in figure 1 represents a brief initial decaying conductance indicating a phenomenon similar to dielectric absorption in solids. It has been suggested that it is due to the orientation of large polarized particles. Region *B* represents the true d-c conductance which is supposed to be due entirely to ions. It is this region which is of one to ten seconds duration in which we are most interested. Region *C* represents the time during which the ions are swept out of the space between the electrodes and space charges built up in the spaces near the electrodes. The empirical nature of the one-minute conductance value is easily understood since it falls in this region. Region *D* represents the long-time conductance after the "clean up" of the oil by the current which may take a period of hours to reach a constant value.

It was desired to find some more practicable and easier method than the amplifier-oscillograph arrangement by which to measure the true d-c conductance of region *B*. It was thought that the velocities of the ions could be reduced by reducing the potential gradient between the electrodes so that the true d-c conductance of region *B* would be extended from ten seconds duration to perhaps ten

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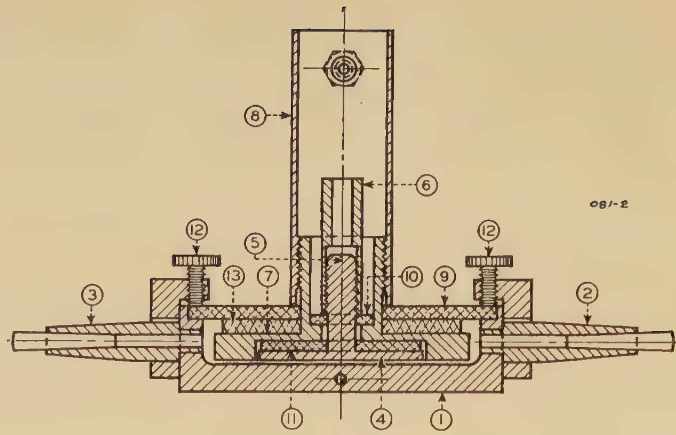
1. For all numbered references, see list at end of paper.

Figure 2. Oil-measuring cell

1—Low electrode
2, 3—Filling arms
4—High electrode
5—Electrode stem
6—Tapped stem
7—Guard electrode
8—Shielding tube
9, 10, 11—Insulators
12—Clamps
13—Pyrex spacer



minutes duration. If, for example, the potential gradient were reduced from the customary 1,000 volts per millimeter to 10 volts per millimeter the duration of the true d-c conductance would be extended from ten seconds to more than ten minutes.

Measuring Cell

It was further desirable to be able to make measurements of the d-c conductance using the same low-capacitance cell (approximately ten micromicrofarads capacitance) used in this laboratory for power-factor measurements. By doing this, both a-c and d-c measurements could be made on the same oil sample under identical conditions of cleaning and filling. This cell is shown in figure 2. It is a three-terminal cell which is so constructed that it may be completely taken apart for purposes of cleaning. The cell used in the work herein reported was made of stainless steel with nickel arms for filling. The cell was cleaned by three washings in technical benzene and then dried for one hour at 100 degrees centigrade with a continuous stream of nitrogen passing through, and finally cooled in a desiccator.

Bridge

Using a General Radio type 544 megohm bridge upon which various alterations had been made so as to increase its range and to allow it to operate at low bridge voltages, it was shown that this type of an arrangement was practicable for use with bridge voltages of from one to ten volts. With various desirable improvements in mind a new bridge was designed and built specifically for the purpose of making conductance measurements. This bridge has the same essential circuit as the General Radio megohm bridge and is shown diagrammatically in figure 3. It consists of a high-resistance Wheatstone bridge with a vacuum-tube amplifier and sensitive galvanometer as a detector. *B* and *N* are high-ratio arms, *B* with a maximum resistance of a megohm and *N* with a maximum of 1,000 megohms. The arm *A* is a decade resistance unit ranging from 0 to 10,000 ohms in 0.1-ohm steps. The measuring cell is placed in arm *P*, the measuring electrode being connected to the high terminal by a shielded lead. The shield of this lead together with the guard ring is connected to the guard terminal which is grounded. The entire assembly is mounted on an aluminum panel and placed in a shielded case, which is also grounded. All switches in the actual bridge circuit are made of low-loss yellow bakelite and connections where perfect insulation is essential are air-insulated bus wires.

The switching arrangement of the bridge is controlled by the switch indicated as *S*. This is a four-pole double-throw switch with the points bent so as to make contacts in the off position as

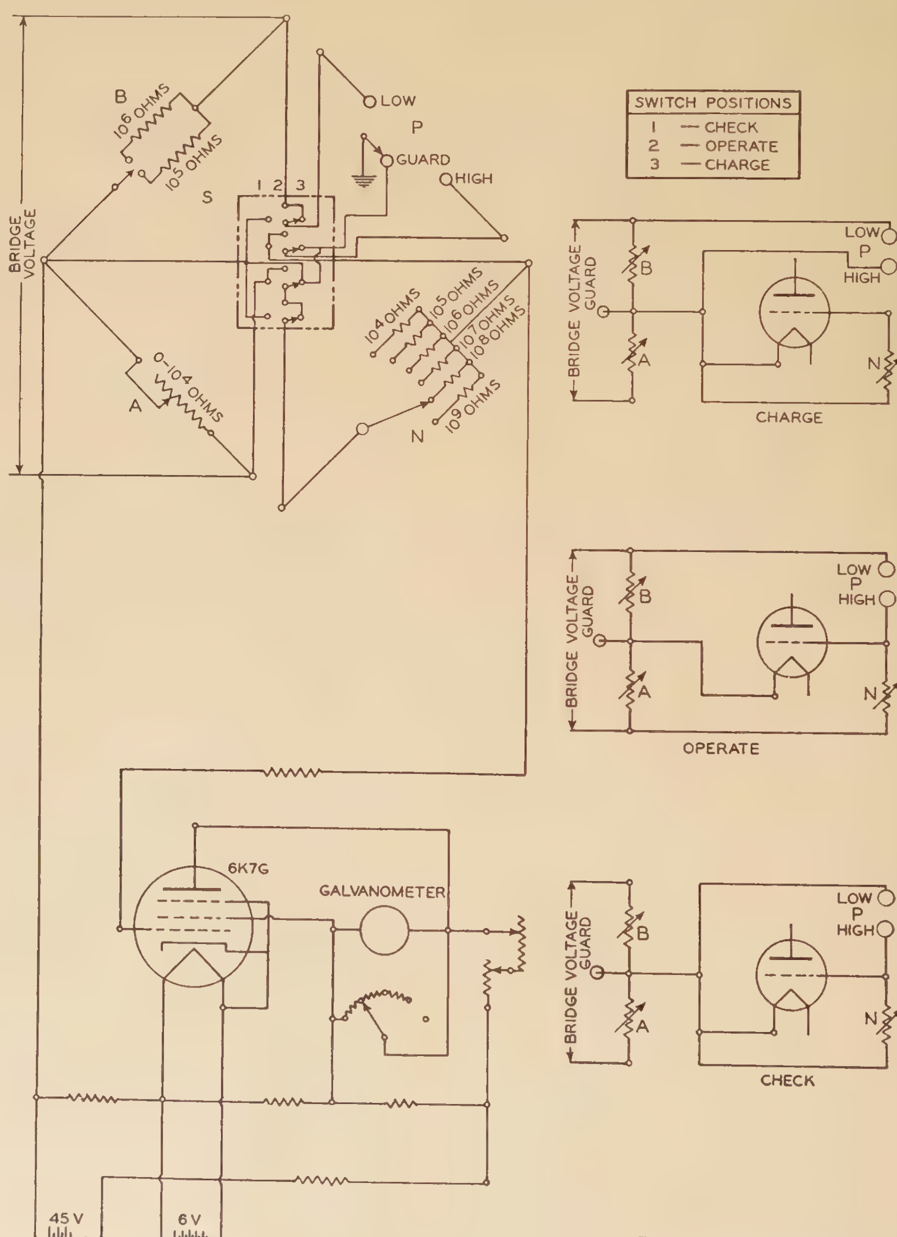


Figure 3. Bridge diagram

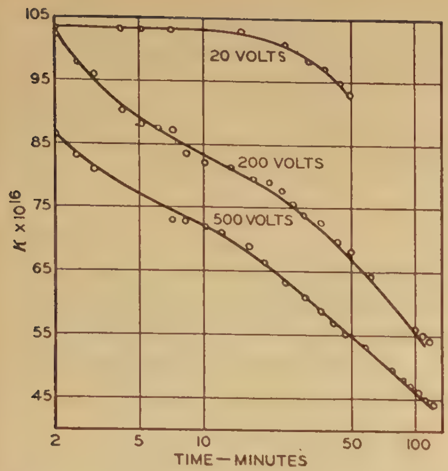


Figure 4. Specific conductance versus time

Table I. Specific Conductances of a Dewaxed Midcontinent Oil at Various Stages of Oxidation

Frequency	Cubic Centimeters O_2 Absorbed						
	0	69	143	187	217	256	328
Direct current	15	26	53	85	133	195	278
40	15	28	47	89	133	218	322
80	16	27	46	83	122	198	296
200	16	28	51	82	117	188	287
400	15	27	49	89	122	204	312
1,000	11	25	43	91	119	210	308

Values—$\kappa \times 10^{14}$; $T = 65$ degrees centigrade.

indicated by connections between the switch terminals. The usual off position then becomes the "operate" position of the bridge. The other two positions are indicated as "check" and "charge" positions. The "check" circuit allows the zero of the detector to be checked and adjusted, at the same time removing the bridge voltage from the measuring arm *P*. The "charge" circuit also allows the zero of the detector to be checked while leaving the bridge voltage across the measuring arm *P* so that measurements may be made from time to time with a continuous application of voltage to the measuring cell. This arrangement allows the time-decay of conductance to be measured from one to two minutes after the application of voltage, that time being necessary for the detector circuit and galvanometer to attain a steady state.

The 0.01, 0.1, and 1 megohm standards are accurate to 0.1 per cent and by connecting the proper open switch terminals of arm *N* to the low terminal of arm *P* it was possible to calibrate the 1,000, 100, and 10-megohm resistors to better than 0.3 per cent. The sensitivity of the detector is such that in measuring a resistance of the order of 10^{14} ohms the error is less than five per cent with about five volts applied. The detector sensitivity limits the value to which the bridge voltage may be reduced; this value also depending upon the resistance value of the oil-filled cell being measured. By the use of a more sensitive detector arrangement the accuracy of the bridge can be increased and the bridge voltage further reduced. It is obvious that the uses of this bridge are not limited to conductance measurements, but that it may also be used to measure almost any type of a high resistance up to 10^{15} ohms.

Guard Circuit

In this bridge the necessity for a conventional shield circuit is circumvented by the use of arms *A* and *B* as a shield circuit. The error in this method is negligible when measuring oils of low conductance and high resistance. However, as the value of the resistance between the guard ring and the low electrode of the cell decreases to approach the value of the resistance in arm *B*, the effective value of *B* will be accordingly affected. Since the resistance between the guard ring and the low electrode acts as a shunt around arm *B*, it is necessary in order to keep the error in arm *B* to less than 0.1 per cent that the value of this shunting resistance should be 1,000 times *B* or about 1,000 megohms. The resistance between the guard ring and the measuring electrode, which shunts around the detector, does not affect the accuracy of the bridge but may affect the sensitivity of the detector. Since the cell used in this work (figure 2) is so designed that the respective resistances between the guard ring and the measuring electrode and the guard ring and the low electrode are approximately the same as the resistance between the measuring and low electrodes, this guard circuit is quite satisfactory, and has the advantage of allowing measurements to be made rapidly. If it were desired it would be a comparatively simple matter to install a conventional shield circuit in the bridge.

Experimental Results

Two methods were chosen to show the value of low-voltage d-c measurements on electrical insulating oils. First, the change of d-c conductance with time was measured at various voltages and second, d-c measurements were compared with a-c measurements on the same oil sample. Through an inspection of these data, a few examples of which are presented here, a definite idea was obtained of the value of this type of a measurement.

Figure 4 shows the specific d-c conductances plotted against time for a heavy, dewaxed, solvent-refined, midcontinent oil[3] with bridge voltages of 20, 200, and 500 volts. It will be noted that with 20 volts per millimeter gradient (the cell spacing being 1.04 millimeters), a constant conductance was observed for a period of 15 minutes, while in the case of the higher potentials of 200 and 500 volts the conductance decreased rapidly with time from the initial two-minute reading. It is believed that these curves are thus an excellent confirmation of the theory expressed above, namely, that by reducing the potential gradient in the oil the velocity of the ions would be so reduced that the constant

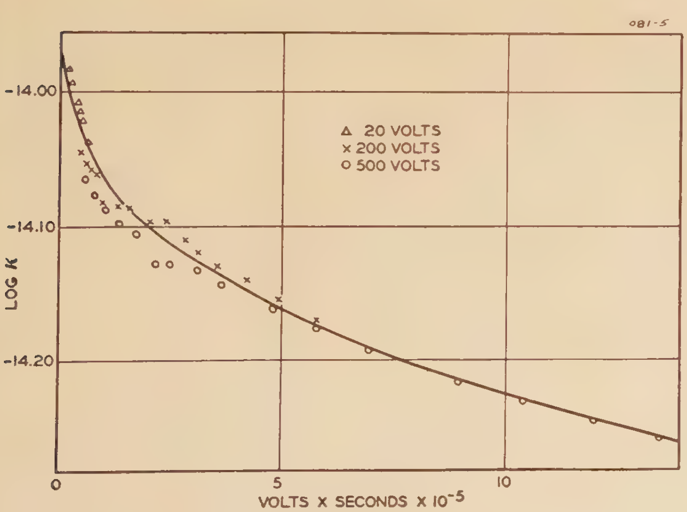


Figure 5. Logarithm of specific conductance versus (voltage × time)

conductance of region B in figure 1 would exist for a much longer period of time. This interpretation of these curves would lead us to conclude that low-voltage measurements of this type do measure the true d-c conductance of electrical insulating oils.

Figure 5 shows a plot of the logarithm of the specific d-c conductance (κ) of the same oil against the product of voltage (V) and time (t). For all three voltages the points fall along the same curve, showing that the conductance change depends upon the quantity of electricity passed through the oil. If we assume that this decrease in conductivity is due entirely to the discharge of ions at the electrodes, we can, by the use of certain other assumptions calculate the mobilities of the ions involved from the slope ($d \log_e \kappa/d(Vt)$) of a curve such as shown in figure 5. For this oil mobilities varying from 8×10^{-10} to 3×10^{-8} cm^2 sec^{-1} $volt^{-1}$ were thus obtained. These mobilities are of a reasonable order of magnitude, and these investigations are being continued.

Using the power-factor bridge[4] which has been developed in this laboratory, power-factor measurements were made on the same oil samples on which d-c measurements were made. By the use of the formula

$$\kappa = 0.556\times10^{-12}\nu \tan \delta C/C_0$$

where δ is the loss angle, C and C_0 are the capacitances of the cell with oil and air respectively as dielectrics, and ν is the frequency in cycles per second at which the measurement is being made, specific a-c conductances were computed for purposes of comparison with d-c values. Table I gives the specific conductances of a low-viscosity distillation cut of a midcontinent crude[5] at various stages of oxidation at 65 (± 1) degrees centigrade. On inspection of these data it will be seen that there is, in general, good agreement between the d-c and a-c values, the average deviation from the mean being about five per cent. The deviations were thought to be due largely to fluctuations in temperature, and these fluctuations will be reduced in subsequent work. However, it is considered that these data do definitely show that the a-c losses are, in the case of this oil, wholly due to the same type of a loss which gives a d-c conductance and which is generally considered to be the result of ionic conductance. This type of a comparison is now being made on other oils that are being investigated in this laboratory. Since by this type of a comparison, low-voltage d-c measurements do account for all of the a-c losses it may again be concluded that the low-voltage measurements herein described do measure the true d-c conductances of electrical insulating oils.

Summary

1. Apparatus has been developed which is suitable for the measurement at low voltages of the d-c conductances of electrical insulating oils.

2. The change of d-c conductance with time of a highly refined oil has been found to substantiate the theory that low-voltage methods do measure the true d-c conductance of electrical insulating oils.

3. The change in the conductance of this oil is shown to be a function of $V\times t$, V being the applied voltage, and t the length of time of application.

4. D-c measurements have been compared with a-c measurements on a low-viscosity oil and low-voltage d-c measurements have been shown to account for all of the a-c loss in the oil thereby again leading to the conclusion that the low-voltage methods developed in this paper do measure the true d-c conductance of electrical insulating oils.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Rapid-Recording A-C Bridge

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THIS paper describes a rapid automatic recording a-c bridge for continuously recording the power factor and capacitance during life runs or short-time tests on cables, capacitors, and insulating materials at a frequency of 60 cycles per second.

During the manufacture of electrical insulating structures and also during such extreme variations in conditions as occur on accelerated life tests, changes occur in the dielectric power factor and in the capacitance which are not fully reversible. A full record of such changes may be expected to contribute toward an understanding of the factors leading to failure under operating conditions. Data of this type in the past, generally were obtained manually, plotting point-by-point measurements made on a manual bridge. It is often desirable to obtain records of rapid changes which occur faster than can be recorded by this method. The automatic bridge described here rapidly records any change in the test specimen and is capable of operation 24 hours a day without attention. A photograph of the complete equipment is shown in figure 1.

A block diagram of the equipment is shown in figure 2. Referring to this diagram, a Schering bridge is used to measure capacitance and power factor. The voltage across the detector diagonal of the bridge, indicating bridge unbalance, is amplified and impressed upon circuits sensitive to components of the unbalance voltage produced by capacitance change and power-factor change respectively in the test specimen. These phase-sensitive circuits, called "phase selectors," control two thyratron circuits which supply power to two motors. The motors are coupled to adjustable circuit elements in the arms of the Schering bridge so that the unbalance voltage is reduced to zero and the motors are de-energized. Thus, the bridge is automatically balanced for the new values of capacitance and power factor which the test specimen has assumed. The time required for this operation is about one second. To prevent motor travel beyond the balance point because of the inertia of the motor arma-

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tures and the associated moving parts, an antihunting feature is built into the equipment.

The new positions assumed by the circuit elements are indicated on the capaci-

Figure 1. Rapid-recording a-c bridge

tance and the power-factor recorders, the pens of which are electrically coupled to, and move in unison with, the shafts of the bridge-circuit elements. The scales are marked directly in capacitance increase and in power factor. The recording Schering bridge consists of the following units:

1. Schering bridge
2. Voltage amplifier
3. Phase selectors
4. Thyratron circuits and motors
5. Antihunting circuits
6. Recorders

The following is a brief discussion of the circuits and the principle of operation of each unit.

Schering Bridge

The Schering bridge is the conventional one shown in figure 3. A fixed resistor R_4 is shunted by an adjustable capacitor, and connected in series with a high-voltage standard capacitor, C_1. R_3 is a manually adjustable resistor in series with the specimen capacitor. Power-factor balance is obtained by setting the adjustable capacitor for balance. Capacitance change in the specimen is measured by adjusting a tap on a slide-wire resistor shunting the R_3 resistor until bridge balance is obtained. Guard circuit potential is adjusted by setting the resistor F to the point which allows push button B to be operated with no change in the "capacitance change" balance.

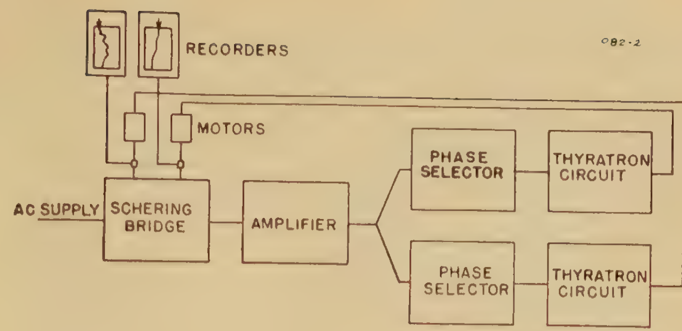


Figure 2. Block diagram of complete automatic bridge

A choice of several fixed resistance values at R_4 and a manually-operated step capacitor in parallel with the adjustable capacitor provide a means for selecting a power-factor range suited to the specimen tested. Range widths on the present bridge are 0.01, 0.02, and 0.05 tangent loss angle, which is approximately equal to the power factor or the sine of the loss angle. By use of the step capacitor, tangent loss angle as large as 0.3 may be measured, in which case the range covered by the recorder chart will be 0.25 to 0.30 tangent loss angle. Capacitance changes for full chart width deflection are $2^1/_2$, 10, 25, and 100 per cent. When used with a 100-micromicrofarad standard capacitor, capacitances from 50 to 10,000 micromicrofarads can be measured. Larger capacitances may be measured with the aid of external shunts. A photograph of the motor-operated Schering bridge unit is shown in figure 4.

It is possible to test several specimens in succession by providing an adjustable resistor in series with each and a time switch for connecting the slide wire at R_3 successively to each.

Voltage Amplifier

The function of the amplifier is to increase the feeble unbalance signal appearing at the output of the bridge when unbalance occurs, so that sufficient voltage is available to operate the phase-selector circuits. With a few exceptions, it is a conventional three-stage amplifier with resistance and capacitance inter-stage coupling and transformer input, as shown in figure 5. A photograph of the amplifier and phase-selector unit is shown in figure 6.

For proper operation of the phase-selective circuits which follow the amplifier, the phase shift in the amplifier must be either zero or an integral multiple of 90 degrees and the output voltage must be relatively free from harmonics. Control of both is obtained by the insertion of resistance-capacitance attenuators R,C between stages. The need for these effects is explained later.

Series resistances are inserted in the leads to the grids of the second and third stages to minimize parasitic phase shifts. To minimize changes in amplifier performance produced by changes in tube characteristics if the tubes overload, all plate load resistances are chosen low. Amplifier sensitivity is controlled manually by potentiometer resistors in the grids of the first two stages.

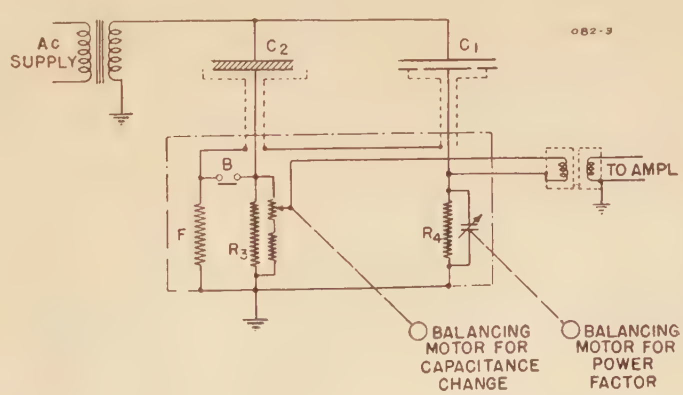
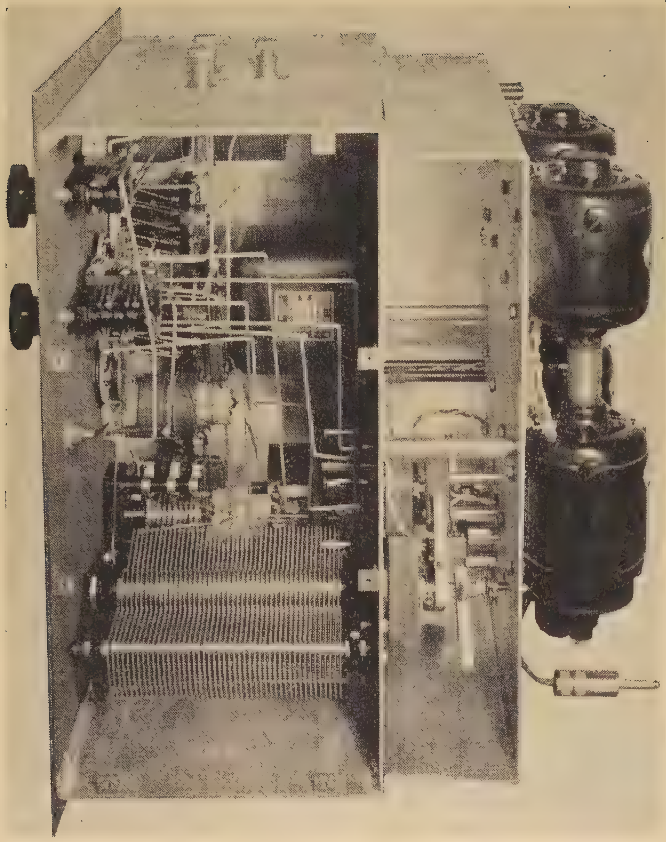


Figure 3. Circuit diagram of Schering bridge unit



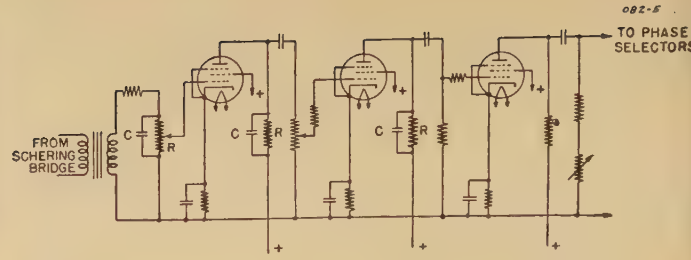


Figure 5. Circuit diagram of amplifier unit

Figure 4 (left). Rapid-recording a-c bridge; Schering bridge unit

voltage, all tubes pass current during a portion of the cycle and the average direct voltage across the output terminals is zero. Under this condition, the other phase-selector circuit is actuated. The phase selector not described is identical except a 90-degree phase-shifting network is inserted ahead of the signal input transformer T.

The phase selector is not affected immediately by harmonics of the applied voltage, but it is necessary partially to filter out the harmonics present in the bridge unbalance voltage to avoid overloading the amplifier with these harmonic voltages, thereby decreasing the response to the fundamental bridge unbalance voltage.

Phase Selectors

The function of the phase selectors is to separate the voltage components of bridge unbalance produced by capacitance and power-factor changes in the test specimen. The amplified bridge unbalance voltage is simultaneously applied to both phase selectors, but a capacitance unbalance causes one phase selector to function while a power-factor unbalance actuates the other. If both quantities change in the test specimen, both respond. The amplifier and both phase selectors are mounted on one panel as shown in figure 6. For purposes of clarity, only one has been shown in the circuit diagram in figure 7.

The phase selector operates by comparing the phase and magnitude of the amplified bridge unbalance voltage applied to T, with the phase of a reference voltage E_R which is the a-c supply voltage used for the Schering bridge. For this reason, it is important to control the phase shift in the amplifier as noted before.

Assume that a change has taken place such that the signal to the grid transformer T is in phase with the reference voltage E_R which is applied to the plates. Under this condition, for a given signal voltage the phase selector gives its greatest output. For the instantaneous polarities of plate and grid voltage indicated in the diagram, tube 1 passes current during the half cycle that this condition is maintained. During the next half cycle, tube 2 passes current. Thus, a pulsating direct current passes through the common load resistor R_1, producing an average direct voltage across the output terminals leading to the thyratron circuit, the magnitude of which is proportional to the magnitude of the input signal to T. If the signal voltage is 180 degrees reversed, tubes 3 and 4 pass current through R_2, producing a voltage of opposite average d-c polarity across the output terminals. However, if the signal is in quadrature with the reference

Thyratron Circuits and Motors

The function of the thyratron circuits is to supply power to the balancing motors at a rate dependent upon the magnitude of the d-c output of the phase selectors. Both thyratron circuits are contained on one panel shown in the photograph in figure 8. The motors are mounted on the Schering bridge panel shown in figure 4.

A diagram of one of the thyratron circuits is shown in figure 9. The motor is series wound with a divided field winding, each field winding being connected in the plate circuit of a thyratron tube. The grid bias and plate-supply voltages,

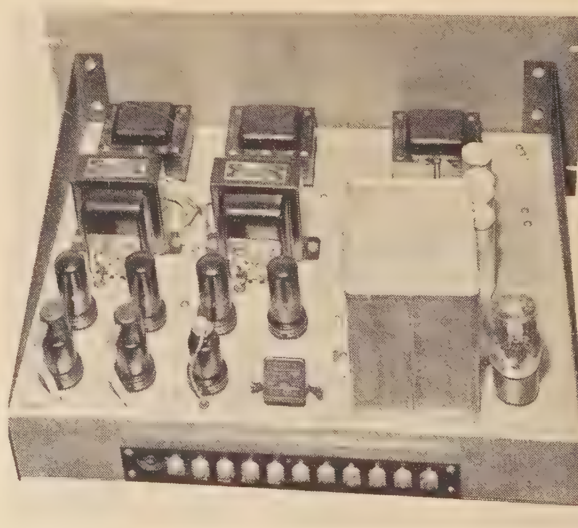


Figure 6. Rapid-recording a-c bridge; amplifier and phase-selector unit

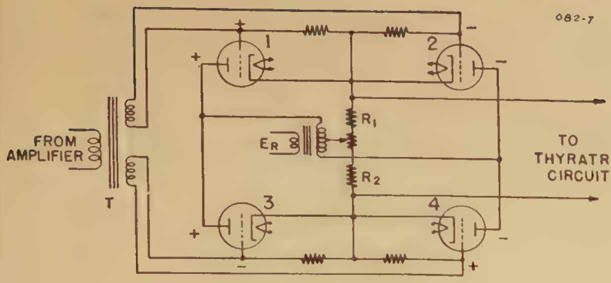


Figure 7. Circuit diagram of phase-selector unit

e_g and e_p respectively, are obtained from the 60-cycle a-c power supply. With d-c excitation on the grids, the tube with a positive grid fires or starts to pass current during each positive half cycle of the a-c supply voltage on its plate. This current persists until the end of the half cycle. If the d-c grid excitation changes polarity, the other tube fires, sending current through the other field winding and causing the motor to reverse direction. Speed of rotation is controlled as follows. For a high value of d-c grid excitation, the tube passes current during the full half cycle. For low excitation, the current impulse is shorter because the tube fires later in the half cycle. Hence, the average current through the motor becomes less and the motor runs more slowly.

The operation of the thyratron tube in this circuit can be explained as follows. The capacitor C_4 in the grid-bias transformer T_2 produces a constant phase shift in the alternating bias voltage e_g which lags the plate voltage e_p by about 90 degrees as shown in figure 10. Under this condition, the grid is at no time sufficiently positive to cause the tube to fire. With a slight positive d-c grid excitation superimposed upon the a-c bias, e_g is raised high enough to cause the tube to fire during the latter part of the positive half cycle of e_p. With increased d-c excitation, e_g is raised still higher so that the lowest point in this curve becomes sufficiently positive to cause the tube to fire, and the tube passes current for the full half cycle. Thus, regulated control of motor speed, depending upon the magnitude of the grid excitation voltage, is obtained.

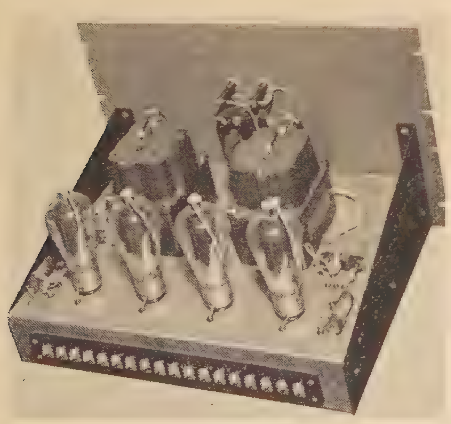


Figure 8. Rapid-recording a-c bridge; thyratron unit

Antihunting Circuit

The function of this circuit is to prevent hunting produced when the inertia of the motor and associated rotating parts cause the motor to follow through or overshoot the correct position when the bridge balance is reached, thereby unbalancing the bridge in the reverse direction and setting up an oscillating condition.

A resistor R_5 and capacitor C_5 shown in figure 9 are inserted in the signal input lead to the thyratron circuit. These build up a temporary d-c potential in series with the signal voltage and opposite in polarity. This reduces the effective voltage at the thyratron grids and causes it to drop to zero slightly before the bridge has actually reached balance. The motor, by virtue of its inertia, then tends to coast to the proper position. Should the motor not stop at the correct position, the antihunting voltage quickly drops to zero, the signal voltage again takes effect, and the motor receives an additional impulse which finishes the balancing operation.

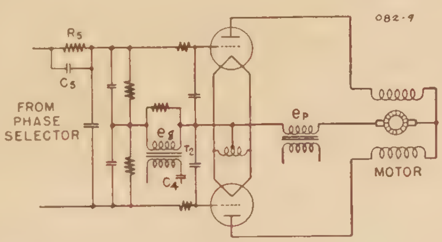


Figure 9. Circuit diagram of thyratron unit

Recorders

The function of the two recorders is to follow the position of the capacitance and power-factor balancing elements in the Schering bridge, thereby recording the capacitance and power factor of the test specimen as a function of time.

Each recorder has a separately excited ratio-type instrument movement excited from the a-c supply line through a resistance potentiometer mechanically coupled to the shaft of the balancing element in the bridge. The line voltage can vary as much as 20 per cent without affecting the indication. Chart speeds of one inch per minute and one inch per hour are provided.

Switches for changing bridge range, giving an alarm, or discontinuing the test may be located on the balancing elements to handle specimen changes larger than anticipated.

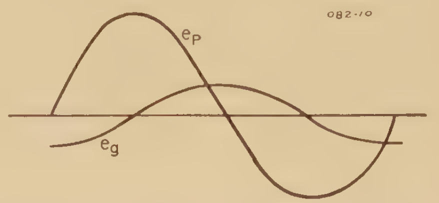


Figure 10. Grid and plate voltage relationship, thyratron unit

Summary

A power-factor and capacitance bridge capable of unattended recording has been described. Changes in the specimen may be fully recorded within one second of their occurrence.

The bridge may be used in connection with life tests, during treating processes, and for recording tests on large numbers of nominally identical structures, in the process of production.

The automatic control circuits described in this paper are not limited only to application to the Schering bridge, but may be used for automatic balancing of practically any other type of a-c bridge as well.

References

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2. An Automatic A-C Potentiometer and Its Application to the Nondestructive Testing of Insulating Equipment, George Keinath. AIEE Transactions, volume 58, 1939, pages 887–90.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Effect of Load Factor on Operation of Power Transformers by Temperature

V. M. MONTSINGER
FELLOW AIEE

Synopsis: The practice of loading transformers by temperature is growing among operators who desire to take advantage of the additional capacity offered by this method of loading. The standards now recognize continuous overloads in cool ambients and short-time overloads under recurrent and emergency conditions.

The paper discusses the effects of different shapes of system load factors on the aging of the insulation. Then the ones that result in the greatest amount of aging are used for determining the permissible peak loads that can be carried safely with the same deterioration of its insulation as results from continuous operation at rated kilovolt-amperes.

A rational method of calculating the hot-spot temperature is shown by means of examples using a general average "time constant". The hot-spot temperature curve is then integrated to compare the aging with a given constant temperature.

From these results it is concluded that a normal power transformer can be overloaded 3 per cent for each 10 per cent that the system load factor is below 100 per cent. That is, for a 50 per cent load factor the permissible peak load is 15 per cent over the transformer rating in a standard ambient. For low ambients where 1 per cent overload for each degree that the ambient is below 30 degrees is now permitted, the permissible peak loads will vary depending on ambient and on load factor. By combining the 3 per cent rule for load factor and 1 per cent rule for ambient, proposed loading curves are shown for different load factors and different ambients.

SEVERAL papers have been written[1,3,5] on the operation of transformers by temperature during the past several years. As a result of these activities, the American Standards Association sectional committee on transformers, C-57 has published "Guides for Operation of Transformers" as an appendix to the proposed American standards for transformers, regulators, and reactors.

These guides give permissible overloads under the following conditions: (1) continuous overloads in cool ambients, (2) short-time overloads under recurrent conditions, and (3) short-time overloads under emergency conditions. These short-time overloads apply to transformers irrespective of the system load factors, and are limited to a few hours duration.

There are conditions under which the maximum load may last for times longer than those permitted for the overloads given in the guides, and where it is safe to carry some overload. It is primarily for this condition that this paper is presented.

Load Factor—Definition

The ASA definition for load factor (35.10.125) is as follows:

"Load factor is the ratio of the average load over a designated period to the peak load occurring in that period".

The ASA definition of peak load (35.10.135) is:

"Peak load is the maximum load consumed or produced by a unit or group of units in a stated period of time. It may be the maximum instantaneous load or the maximum average load over a designated interval of time".

"*Note:* Maximum average load is ordinarily used. In commercial transactions involving peak load (peak power) it is taken as the average load (power) during a time interval of specified duration occurring within a given period of time, that time interval being selected during which the average power is greatest".

Load factor as used in this paper refers to the load on the transformer bank under consideration. It is to be noted that load factor as so defined is to be distinguished from the ratio of the average load to the transformer rating, as this latter ratio is, by ASA definition, "capacity factor".

Very few power transformers operate at 100 per cent load factor, the majority of load factors being in the order of 50 to 70 per cent.

There are in general three types of loads, industrial, residential, and combined industrial and residential, all of which generally have load factors well below 100 per cent. Figures 1, 2, and 3 are good illustrations of such loads. These load factors are 51.5 per cent, 55 per cent, and 60.5 per cent respectively, based on peak loads of one-half hour, instead of on the extreme peaks.

Effect of Load Factor on Permissible Output

It is, of course, obvious that a transformer operating under low-load-factor conditions can carry some overload under peak load conditions with the same degree of aging of its insulation as one carrying rated load continuously. The problem is to determine the amount of overload that will give the same aging, for different load factors. To do this requires: (1) determination of the hottest-spot temperature during one complete 24-hour period, and (2) integration of the hottest-spot temperature curve during the 24-hour period, to obtain the amount of aging of the insulation. When an overload is found (by trial) to cause the same amount of aging as occurs when the transformer is carrying rated load for 24 hours, this represents the permissible overload for that particular kind of load curve.

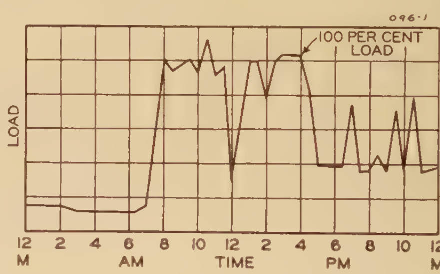

Figure 1. Industrial load; 51.5 per cent load factor

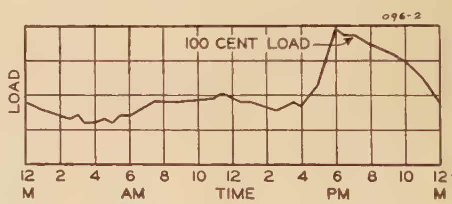

Figure 2. Residential load; 55 per cent load factor

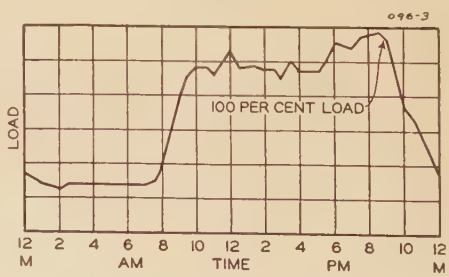

Figure 3. Industrial and residential load; 60.5 per cent load factor

Figures 1–3. Typical load curves on American Gas and Electric Company system

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1. For all numbered references, see list at end of paper.

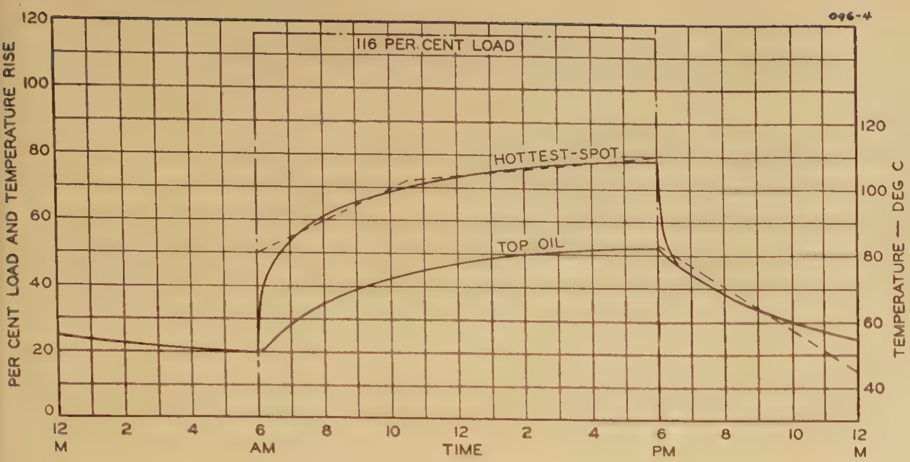


Figure 4. 50 per cent load factor composed of industrial load for 12 hours during 24-hour period

24-hour average load=58 per cent; 30 degrees centigrade ambient

The permissible overload for a given load factor varies over a wide range, depending on the shape of the load curve. For example: a 50 per cent load factor in which 100 per cent load is carried 50 per cent of the time, with no load on the remainder of the time (figure 4) will permit a minimum overload rating, whereas a 50 per cent load factor in which partial load is carried most of the time and a peak load is carried the rest of the time (figure 7) will permit a greater overload rating. The first case might correspond to an industrial 50 per cent load factor condition requiring power during the day, only, and the second case, might correspond to a condition where, during the late evening hours, a heavy residential peak load is superimposed on a light 24-hour load.

Table I

Kva	High-Voltage Kv	B Time Constant
1,000	13.8	2.86
1,000	13.8	2.78
1,000	69.0	4.55
		3.39
2,500	13.8	2.83
2,500	69.0	4.0
2,500	138.0	4.46
		3.76
5,000	13.8	2.32
5,000	69.0	2.64
5,000	110.0	3.70
		2.89
8,333	34.5	3.03
8,333	69.0	3.23
8,333	138.0	4.55
		3.60
20,000	34.5	2.5
20,000	69.0	3.41
20,000	138.0	4.2
		3.37
33,333	69.0	3.03
33,333	115.0	3.20
33,333	138.0	3.65
		3.29

Calculation of Hottest-Spot Temperature

The hottest-spot temperatures are calculated in two stages. First, the top-oil temperature rise is obtained, and then the hottest-spot rise over the oil is determined and added to the top-oil rise. The most difficult part is the calculation of the oil temperature under varying load conditions. When this is done, the rest is easy, since the winding rise over the oil becomes constant in 20 to 30 minutes and can be taken directly from a curve of ultimate rise versus load, and added to the oil rise.

For the particular case under consideration the following assumptions are made, in calculating the hottest-spot temperatures.

1. The ratio of losses at rated load is 2:1 (2 copper, 1 iron).

2. The ultimate top-oil rise at rated load is 45 degrees centigrade.

3. The hottest-spot temperature rise over the top oil is 20 degrees centigrade (10 degrees average rise +10 degrees hot-spot rise over average rise) at rated load, and varies as the load raised to the 1.6 power.[1]

4. The no-load ultimate oil rise is 19 degrees centigrade. (The exact value based on 2:1 ratio of losses at rated load and temperature rise varying as 0.8 power is 18.7 degrees centigrade.)

5. The ultimate oil rise varies as the 0.8 power[1] of the losses.

6. The time constant corresponds to that for the average single-phase power transformer ranging in size from 1,000 to 33,333 kva. Table I.

7. One hundred per cent excitation voltage is on at all times. The time constant is, therefore, based on the copper losses only.

8. The load cycle selected is repeated from day to day such that the oil temperature is the same at the beginning and end of each 24-hour period.

9. A constant ambient temperature of 30 degrees centigrade is maintained.

Tests have shown[5,11] that the oil rise under transient conditions can be estimated quite closely by the exponential formula:

$$\theta_r = \theta_u\left(1 - \epsilon^{-\frac{t}{B}}\right) \quad (1)$$

where

θ_r = temperature rise of oil at any time t
θ_u = ultimate oil rise
ϵ = 2.718
t = time in hours
B = time constant*

$$= \frac{C \times \theta_u}{\text{loss at initial temperature}}$$

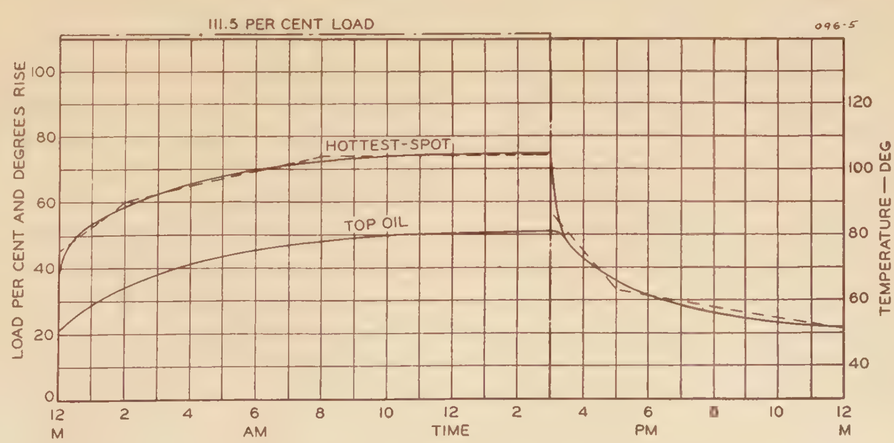
C = thermal capacity of iron core, windings (copper) tank and oil

$$= \frac{3.5 \times \text{pounds (core+copper+2/3 tank)} + 90G}{60}$$

G = gallons oil (United States)

* The time constant is the time required to reach ultimate temperature rise, if all heat were stored in the transformer.

Figure 5. 62.5 per cent load factor; 30 degrees centigrade ambient



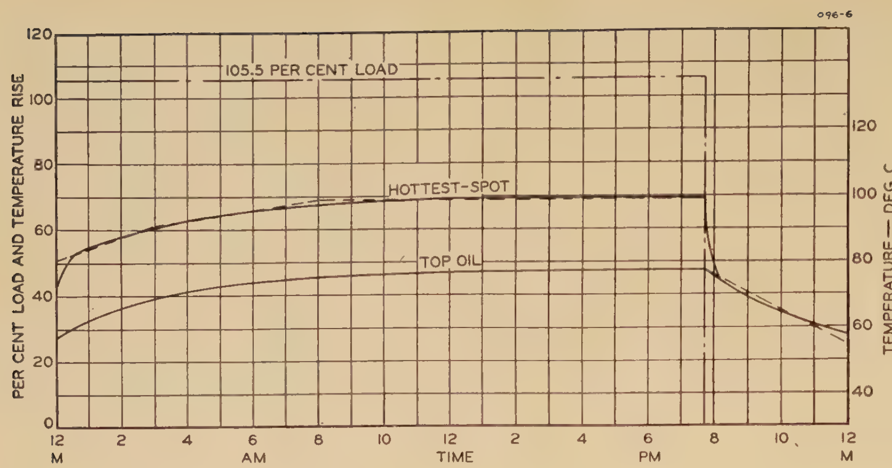


Figure 6. 82 per cent load factor; 30 degrees centigrade ambient

Only 2/3 of the tank is used because the lower third is comparatively cool, and 85.7 per cent (of 105*G* the correct value to use when the oil is at a uniform temperature) of the oil is used for the same reason.

In table I are some representative values of *B* for load (copper) losses only, taken at 110 per cent load. One hundred and ten per cent load was chosen for the reason that the overload periods exert the greatest effect on the life of the insulation, and 110 per cent load is a general average value used for the various load factors.

The average of the values of *B* in the table is 3.38. A general average value of 3.33 appears to be a reasonable one to use. It is proper to point out, however, that *B* varies to some extent for different oil rises for the reason that the oil rise is not proportional to the losses but varies as the 0.8 power of the losses. Tests show,[5] however, that results close enough for practical purposes are obtained by using an average value of *B* for the oil rises under consideration.

Equation 1 applies to oil-temperature rises. When the oil temperature is cooling down, the following equation applies:

$$\theta_c=\theta_i\left(1-\epsilon^{-\frac{t}{B}}\right) \qquad (2)$$

Where

θ_c = cooling in degrees during time period t
θ_i = initial oil rise over the ultimate for the load under consideration (that is, for no-load condition following some given load, θ_i is the initial oil rise minus 19 degrees centigrade)
t = time in hours
B = 3.33

Calculation of Top-Oil Rise for a Given Load Factor

Figures 4, 5, and 6 show three assumed load curves in which the maximum loads are on for 50 per cent, 62.5 per cent, and 82 per cent of the time—no load being on the rest of the time. The loads are, therefore, 50, 62.5, and 82 per cent respectively. Figure 7 shows load curve with a 50 per cent load factor, made up of a 51.5 per cent load for 19 hours, and 140 per cent load for 5 hours representing a peak residential overload from 5 to 10 p.m.

As an illustrative case, the top-oil rise will be calculated for the 50 per cent load factor, figure 4.

It was found by trial that the oil rise is 25 degrees at the beginning and end of the 24-hour period. This gives a starting point of 25 degrees centigrade rise at 12 midnight.

From 12 to 6 a.m., the oil is cooling down. Using equation 2 we have (when t=6 and the ultimate no-load oil temperature rise is 19 degrees centigrade)

$$\theta_c=\left(25-19\right)\left(1-\epsilon^{-\frac{6}{3.33}}\right)=5.0 \text{ degrees centigrade}$$

Therefore, at 6 a.m. the oil rise has dropped from 25 to 20 degrees centigrade.

At 6 a.m. 116 per cent load comes on and the oil temperature starts to rise. The ultimate oil rise for 116 per cent load is 53 degrees centigrade. The oil rise at any time from 6 a.m. to 6 p.m. is estimated by equation 1, or

$$\theta_r=\left(53-20\right)\left(1-\epsilon^{-\frac{t}{3.33}}\right)$$

Following are the oil rises, for different times t

Time	7 a.m.	10 a.m.	2 p.m.	6 p.m.
t =	1	4	8	12
θ_r =	8.6	23	30	32.0 over 20 degrees rise (starting at 6 a.m.)

From 6 p.m. to 12 midnight, the oil temperature again decreases:

$$\theta_u=(52.0-19)\left(1-\epsilon^{-\frac{6}{3.33}}\right)=27.0 \text{ degrees}$$
or 52.0−27=25.0 degrees centigrade rise at 12 midnight

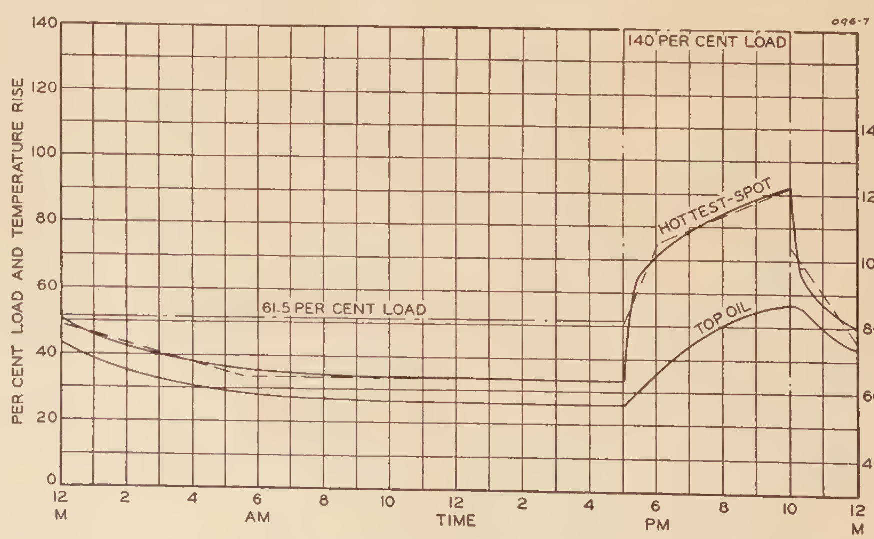
Adding 30 degrees centigrade ambient to the above values, we obtain the top-oil temperature as shown in figure 4.

The next step is to add the winding hottest-spot to the top-oil temperature curve shown in figure 4. The ultimate winding hottest-spot rises over the oil versus load are shown in figure 8, assuming 20 degrees rise at rated load.

The hottest-spot curve figure 4 is divided into trapezoids (dashed lines), for the purpose of integrating the area to determine the aging during a 24-hour period.

Figure 7. 50 per cent load factor, composed of light industrial and peak residential load

24-hour average load=70 per cent; 30 degrees centigrade ambient



As shown in a previous paper,[10] the aging may be computed by the following equations:

For a constant temperature

$$A = t\epsilon^{kT} \tag{3}$$

where

A = aging units
ϵ = 2.718
T = temperature degrees centigrade
k = 0.0865—which doubles the aging for each 8-degree-centigrade increase in temperature

For a trapezoid in which the two unequal sides represent temperature

$$A = t\left[\frac{\epsilon^{kT_2} - \epsilon^{kT_1}}{k(T_2 - T_1)}\right] \tag{4}$$

where

T_2 = the maximum temperature degrees centigrade
T_1 = the minimum temperature degrees centigrade

As previously stated, the load-cycle conditions have been selected such that the aging will be the same as that under continuous rated load conditions. For a 24-hour period, the aging at 95 degrees centigrade (55 rise by resistance+10 degrees hottest-spot+30 degrees ambient) is by equation 3

$A = 24\epsilon^{0.0865\times 95}$ 87,500 units

Integrating the hottest-spot (dashed) curve in figure 4, the aging by equation 4 is

$$A_1 = 6\left[\frac{\epsilon^{0.0865\times 55.0} - \epsilon^{0.086\times 550}}{0.0865(55.0-50)}\right] = 570$$

$$A_2 = 4.5\left[\frac{\epsilon^{0.0865\times 102} - \epsilon^{0.0865\times 80}}{0.0865(102-80)}\right] = 13{,}650$$

$$A_3 = 7.5\left[\frac{\epsilon^{0.0865\times 110} - \epsilon^{0.0865\times 102}}{0.0865(110-102)}\right] = 70{,}000$$

$$A_4 = 6\left[\frac{\epsilon^{0.0865\times 83} - \epsilon^{0.0865\times 45}}{0.0865(83-45)}\right] = 2{,}320$$

Total 86,540 units

The figure 86,540 is close enough to 87,500 units since a change of one degree centigrade affects the aging approximately 12.5 per cent—based on the rate of aging doubling for each eight-degree-centigrade increase in temperature.

It is well to point out that "integration by parts" of the hot-spot temperature curve gives approximately correct results. That is, if in figure 4 the "time" is divided into one hour and one-half hour intervals (depending on the rate of change of temperature) and the average of these time interval hot-spot values is used for T in equation 3, the total aging units obtained are 86,980 which are within 0.5 per cent of those obtained by equation 4. In fact, when the hot-spot curve is quite irregular, the method of "integration by parts" is simpler and probably more accurate.

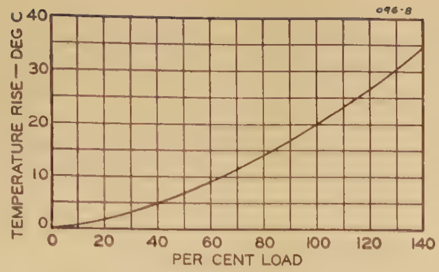


Figure 8. Hottest-spot winding rise over top oil

The aging of figure 7 is by equations 3 and 4:

$$A_1 = 5.5\left[\frac{\epsilon^{0.0865\times 79} - \epsilon^{0.0865\times 64}}{0.0865(79-64)}\right] = 2{,}800$$

$$A_2 = 11.5\times\epsilon^{0.0865\times 64} = 2{,}890$$

$$A_3 = 1\left[\frac{\epsilon^{0.0865\times 105} - \epsilon^{0.0865\times 80}}{0.0865(105-80)}\right] = 3{,}570$$

$$A_4 = 4\left[\frac{\epsilon^{0.0865\times 121.5} - \epsilon^{0.0865\times 105}}{0.0865(121.5-105)}\right] = 75{,}000$$

$$A_5 = 2\left[\frac{\epsilon^{0.0865\times 105} - \epsilon^{0.0865\times 75}}{0.0865(105-75)}\right] = 6{,}400$$

Total 90,660 units

Again, 90,660 units is close enough to 87,500 units—the aging at 95 degrees centigrade for 24 hours.

From the above results, it can be seen that the permissible overload for a 50 per cent load factor ranges from 16 per cent (figure 4) to 40 per cent (figure 7) depending on the character of the overload.* With shorter than five-hour peak loads imposed on partial load conditions, the permissible overload would be greater than 40 per cent. For a one or two-hour peak load, the permissible overload, considered only from the standpoint of aging, might be as high as 80 to 100 per cent. These heavy overloads might not be safe. In the first place, there are often limits other than aging of the insulation, such as overheating of lead joints (when soldered) and ratio-adjuster contacts, regulation, etc. In the second place, it has been shown[13] that when cellulose is maintained at temperatures above approximately 120 degrees centigrade chemical deterioration becomes an important factor.

Under a condition of this kind the short-time heavy overload should be limited to the time specified in the ASA guides. For example if, when following 50 per cent load, the overload was 1.4 times the rated load current the time should be limited to approximately 25 minutes for recurrent conditions and to approximately 100 minutes for emergency conditions.

General rules for overloading transformers should be safe for the worst condition, as one is not sure of the conditions under which these rules will be used.

An integration of the hottest-spot temperature curves shown in figures 5 and 6 gives maximum peak loads of 111.5 per cent with 62.5 per cent load factor and 105.5 per cent with 82 per cent load factor.

It is recognized that with water-cooled transformers the aging under low load factor might be more than for self-cooled transformers, because the oil temperature will respond more quickly to load changes. The difference, however, will not be very great since the faster oil cooling will partially compensate for the faster oil heating up.

The ASA recommended overloads as covered in the guides for operation of transformers, limits two-hour recurrent overloads to 10 per cent and 20 per cent, following full-load and no-load conditions respectively; also, emergency two-hour overloads are limited to 25 per cent and 40 per cent respectively.

The object of presenting the data in this paper is not to replace or supersede the ASA's recommendations which are

Table II. Permissible Loads for Self-Cooled Transformers (Per Cent of Rated Capacity)

Per Cent Load Factor	Ambient Temperature (Deg C) 0	5	10	15	20	25	30
50	145	140	135	130	125	120	115
60	142	137	132	127	122	117	112
70	139	134	129	124	119	114	109
80	136	131	126	121	116	111	106
90	133	128	123	118	113	108	103
100	130	125	120	115	110	105	100

* For the load curves shown in figures 1, 2, and 3, the permissible overloads are in the order of 25 per cent to give the same aging as for continuous operation at rated loads. In other words, the rating of the transformers could be 80 per cent of the peak loads.

Table III. Permissible Loads for Water-Cooled Transformers (Per Cent Rated Capacity)

Per Cent Load Factor	Ambient Temperature (Deg C) 0	5	10	15	20	25
50	140	135	130	125	120	115
60	137	132	127	122	117	112
70	134	129	124	119	114	109
80	131	126	121	116	111	106
90	128	123	118	113	108	103
100	125	120	115	110	105	100

not directly coupled with load factor, but rather to show what is possible under different load-factor conditions, and (most important) to point out the limitations to the use of overloads for various load factor conditions. Several utility engineers are calculating[7,8,9] the permissible overloads on distribution transformers under various conditions of service, and it is the hope that this paper will be of some benefit in these efforts.

We have seen that under the most severe conditions 16 per cent overload can be held on a transformer operating at its maximum load 50 per cent of the time, that is, 50 per cent load factor, figure 4. For 62.5 per cent and 82 per cent load factors shown in figures 5 and 6, 11.5 per cent and 5.5 per cent overloads respectively can be held.

Expressed in terms of load factor, we have:

Figure	Per Cent Load Factor	Per Cent Overload	Per Cent Overload for Each 10 Per Cent Reduction in Load Factor Below 100 Per Cent
4	50	16	3.2
5	62.5	11.5	3.07
6	82.0	5.5	3.05

It appears, therefore, that a safe rule would be to permit 3.0 per cent overload for each 10 per cent that the load factor is under 100 per cent. Approximately the same overload values were obtained in my 1930 AIEE paper,[1] although a different method of calculation was used.

As a result of my 1930 paper, the rule which allows one per cent continuous overload for each degree centigrade that the ambient is under 30 degrees centigrade for air, and 25 degrees centigrade for water, was incorporated in AIEE publication No. 100. The one per cent rule is now in the ASA Guides for Operation of Transformers.

This information will permit taking advantage of both low load factor conditions and low ambient conditions, in cases where this seems advisable.

The proposal is to combine the three-per cent rule and the one-per cent rule which will give the permissible peak loads in per cent of normal rating for low load factors and low ambients as shown in tables 2 and 3 for self-cooled and water-cooled transformers respectively.

The values shown in tables II and III are plotted in curve form in figures 9 and 10. It is not intended that these overloads relating to load factors, be added to the short-time overloads already permitted by the ASA Guides for Operation of Transformers.

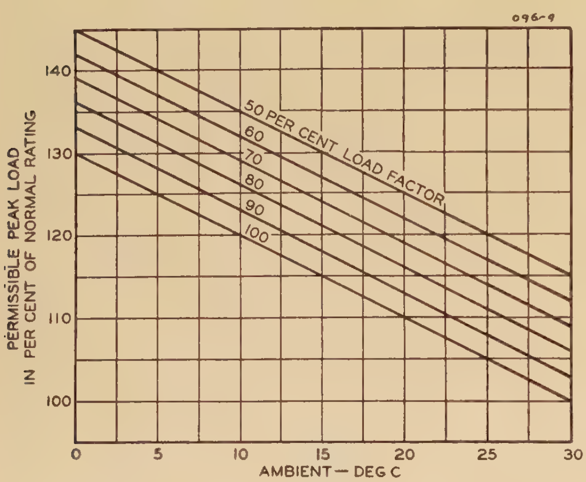


Figure 9 (left). Loading curves for self-cooled transformers

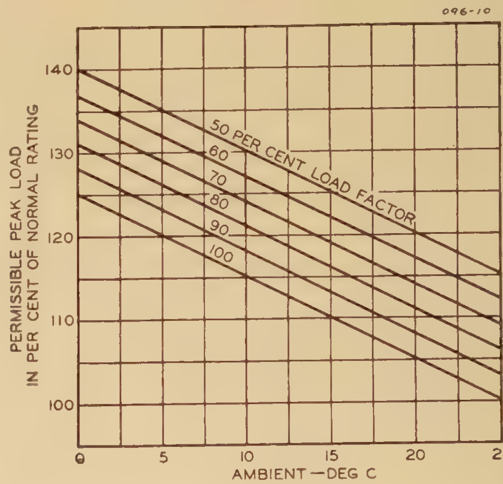


Figure 10 (right). Loading curves for water-cooled transformers

Future Work

To complete the work on loading power transformers by temperature, it is planned to present, at some future date, a paper showing how to convert any load cycle consisting of short-time high peak loads to the equivalent rectangular load cycle, and then limit its duration to the time given by the ASA guides.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 "Transactions Supplement" to Electrical Engineering.

Dead Points in Squirrel-Cage Motors

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Synopsis: Certain squirrel-cage motors are known to have a wide variation in starting torque depending on the angular position of the rotor. In extreme cases the torque may be actually negative at certain positions making the motor entirely useless. Various names such as "dead points," "cogging," and "locking" torque have been used to describe this condition but no detailed study of its mechanism appears to be available.

An analysis of the causes of such behavior is presented here as one of several phenomena not covered by classical theory since they arise from the nonsinusoidal nature of the air-gap field. It is shown (1) that only with certain definite relations of slot numbers can dead points exist at all, and (2) that, given one of these vulnerable slot combinations, the amplitude of the torque variation moves over an extremely wide range as the coil span is changed. The effect of coil span is not merely that due to the numerical change of harmonic chord factor but is shown to be the result of changes of direction of the various component forces. Test results confirming the analysis are included. It now becomes possible to correlate a great many apparently divergent results and to avoid troublesome combinations in future designs.

THE simple elementary theory of squirrel-cage induction motors treats the air gap field as a pure sine wave. Based on this simplification the classical laws of motor performance have been developed. It is evident, however, that in most actual motors the flux field differs sufficiently from a simple sine wave to warrant a closer study of its shape if the performance is to be predicted accurately. For example, the following phenomena depend largely on the nonsinusoidal nature of the flux field.

1. Vibration and noise.
2. Stray load loss.
3. Parasitic torques resulting in

(*a*). Asynchronous cusps in the torque curve.
(*b*). Synchronous locking at low speeds.
(*c*). Dead points or locking at zero speed.

While all of these subjects have been investigated to some extent, the dead-point phenomenon has probably received the least attention and no detailed study of its mechanism is available, at least in the English language. The present paper attempts to fill this gap, offering an explanation of the cause of dead points and some test results that confirm the analysis. It is shown that only with certain definite relations of slot numbers is it possible for dead points or locking torque to exist at all, and, further that the magnitude of the locking torque varies over an extremely wide range as the coil span is changed. While it is admitted that exact quantitative results are difficult to predict, a basis for judging the probability of trouble is established.

Paper 40-101, recommended by the AIEE committee on electrical machinery, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted November 8, 1939; made available for preprinting April 30, 1940.

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1. For all numbered references, see list at end of paper.

Test Observations

A motor which exhibits dead points, or cogging, as it has sometimes been called, will be found to have the following characteristics. The locked-rotor torque varies with the angular position of the rotor, passing through a cycle for each rotor slot pitch. If the running torque is measured slightly above and slightly below zero speed, the torque is found to agree quite closely with the *average* locked value. The locked torque, therefore, is a constant amount plus a variable component which has positive and negative values dependent on the rotor position. The net locked torque may be entirely positive or it may be zero or even negative at certain positions of the rotor. In the latter case the motor is truly "dead" and will not start even without load. However, when the torque is all positive it is only the minimum value that is useful for starting a load. Figure 1 shows tested values of locked torque for a motor of this kind.

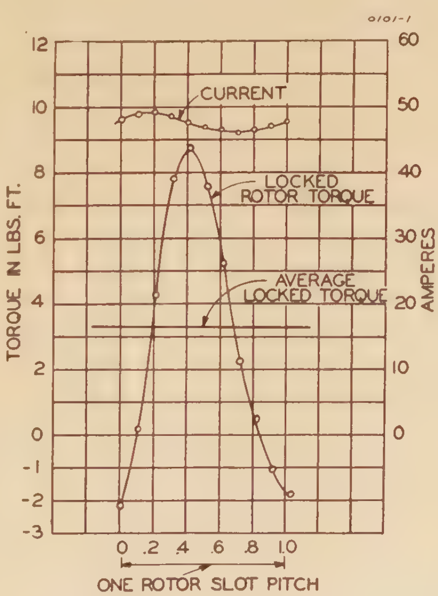

Figure 1. Typical test curve showing variation of locked rotor torque with rotor position

Motor had 24 stator slots, 18 rotor slots, 2 poles, 3 phases, 7/12-coil span, rotor-skewed one rotor-slot pitch

The variable component of torque is similar to the torque of a synchronous machine being dependent on the angular position of the rotor and passing through positive and negative half cycles. One is led therefore to search for a similar cause: two independent fields which are in synchronism at zero rotor speed and have distributions in space such as to give the required torque-angle characteristics. The following discussion shows that the necessary fields are present to fulfil just these requirements.

It has been observed further that motors having the same combination of stator and rotor slots may have widely different amounts of the variable torque component. Since most explanations of this phenomenon have been based heretofore on considerations of permeance variations, the observed results have appeared inconsistent. The analysis given here shows that these results can be explained.

Analysis

1. Stator Harmonics

As with many problems of this kind, it is sufficiently accurate to examine the harmonic fields of stator and rotor which result from the following assumptions:

(*a*). The slot currents are concentrated at points.

(*b*). The air gap permeance is uniform.

For integral-slot stator windings it is well known that the possible harmonics are:

$$n = 1 + MK \tag{1}$$

where M is the number of phase belts per pair of poles, K is any positive or negative integer including zero. The algebraic sign of n shows the direction of travel with respect to the fundamental field. The velocity of each harmonic field is $1/n$th of the speed of the fundamental.

2. Harmonic Fields of Squirrel-Cage Rotors

A squirrel-cage winding carrying currents induced by the fundamental stator

field sets up harmonic fields of the following order in addition to its fundamental field.

$$m = 1 + KS_2 \qquad (2)$$

where S_2 is the number of rotor bars per pair of poles, K is any integer. Usually the only fields having sufficient magnitude to be of importance are those obtained by letting K equal plus and minus one.

This, however, does not complete the list of rotor fields. In addition to currents in the rotor bars induced by the fundamental stator field, there are currents resulting from each of the other stator fields. For each separate current component flowing in the bars there are the following fields:

1. The nth, corresponding to the nth stator field which induced the current under consideration
2. The mth, where

$$m = n + KS_2 \qquad (3)$$

In this case it is usually necessary to consider only the one or two lowest values of m resulting from any given value of n.

3. Comparison of Rotor and Stator Harmonic Fields

It is now possible to set down the harmonic fields of both members and compare them. For purposes of explanation it will be simpler to use an actual case and the one selected is a motor for which test

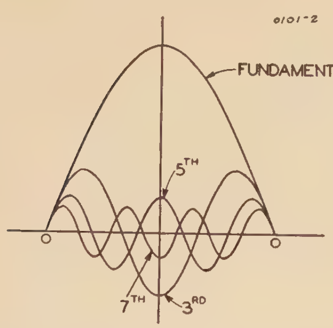

Figure 2. Relation of third, fifth, and seventh harmonics to the fundamental for a single coil

data are available. The specifications are as follows:

Number of poles	= 2
Number of stator slots	=24
Number of rotor slots	=18
Number of phase belts (total)	= 6
Slots semiclosed for both members.	

From these facts and the expressions for stator and rotor harmonics above, the orders of the various fields can be written as shown in table I.

The stator harmonics are simply those that occur in any three-phase motor having an integral-slot winding and the list could be carried out indefinitely. The first column under rotor harmonics is the

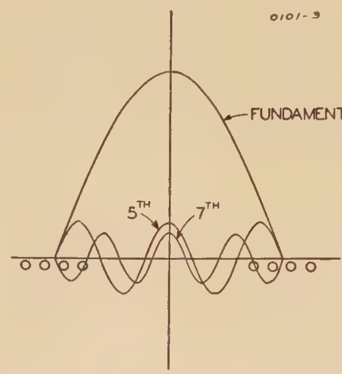

Figure 3. Relation of the fundamental, 5th and 7th harmonics for a three-phase winding with four slots per phase belt and full-pitch coils

series induced by the corresponding stator fields. These combine with the stator fields to produce true induction-motor torques, each with its own synchronous speed, and are of importance in the study of asynchronous cusps. They need not concern us here, however.

The remaining columns of rotor harmonics are the incidental fields set up along with the main fields of column one, their harmonic order numbers being determined by the number of rotor bars. It is these fields that are important in the

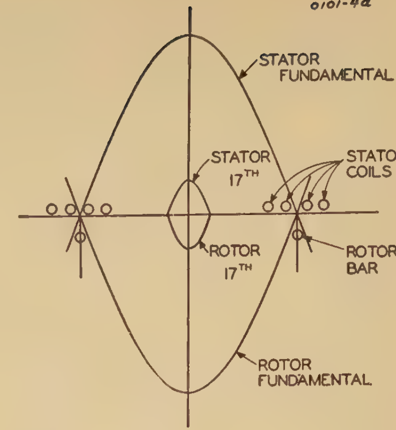

Figure 4a. Relation of 17th-harmonic waves of stator and rotor, for a particular coil span, with rotor in original position

Note: The 17th harmonic is drawn to an enlarged horizontal scale for clearness

present study. It will be noticed that in setting up a secondary field with fundamental distribution we incidentally produce 17th and 19th harmonics which have the same signs as the 17th and 19th stator fields. Thus there is a pair of 17th harmonic fields moving backward at $^1/_{17}$th of synchronous speed but maintaining synchronism with each other while the rotor is at rest, and there is a pair of 19th harmonic fields going forward at $^1/_{19}$th speed under the same conditions. There are, then, steady torques produced by each of these pairs of fields but the direction and magnitude of these torques and their dependence on rotor position will have to be investigated further.

Before going into these questions, however, we can take note of the fact that there are other such pairs of fields present. For each harmonic in the stator column, there is a corresponding harmonic in one or more of the rotor m columns.

4. The Phase Relations Between the Harmonics

In order to proceed with an analysis of the torque components it is first necessary to establish phase relations between the various harmonic fields. Figure 2 shows three of the component fields of a single full-pitch coil in relation to the fundamental. If there are several symmetrical phases of one coil each, this picture also represents the relation between the combined harmonics of all phases at the particular instant when the current in the coil shown is a maximum. It will be noted that those harmonics in the series 1, 5, 9, 13, 17, etc., have positive maximums coinciding. Those in the series 3, 7, 11, 15, 19, etc., have their negative maximums coinciding with the positive

Table I

Stator Harmonics	Rotor Harmonics				
		(K = −1)	(K = +1)	(K = −2)	(K = +2)
n	n	m_1	m_1	m_2	m_2
+ 1	+ 1	−17	+19	−35	+37
− 5	− 5	−23	+13	−41	+31
+ 7	+ 7	−11	+25	−29	+43
−11	−11	−29	+ 7		+25
+13	+13	− 5	+31	−23	
−17	−17	−35	+ 1		+19
+19	+19	+ 1	+37	−17	
−23	−23	−41	− 5		+13
+25	+25	+ 7	+43	−11	

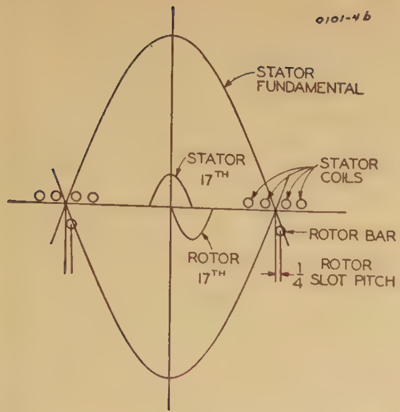

Figure 4b. Relation of stator and rotor 17th-harmonic waves after rotor has been moved one-fourth of a rotor-slot pitch

Table II. Magnitude of Torque Components for Different Coil Spans

n	m	Coil Span as a Fraction of Full Pitch 5/12	6/12	7/12	8/12	9/12	10/12	11/12	12/12
1	17	−11.70	+7.27	+ 1.15	−7.27	+7.27	−1.93	−4.52	+7.27
1	19	− 1.71	+8.42	−10.55	+8.42	−3.42	−2.24	+6.57	−8.42
5	13	− 0.27	+1.37	+ 1.28	−1.37	−0.19	+0.36	−1.13	+1.37
5	23	− 1.20	+5.70	− 7.12	+5.70	−2.26	−1.50	+4.52	−5.70
7	11	− 2.07	−1.00	− 0.17	−1.00	+0.41	+0.24	+0.58	+1.00
7	25	− 5.26	+3.38	+ 0.56	−3.38	+3.20	−0.85	−1.97	+3.38
11	7	− 1.47	−0.58	− 0.05	−0.58	+0.26	+0.15	+0.38	+0.58
13	5	− 0.15	+0.53	+ 0.49	−0.53	−0.07	+0.13	−0.41	+0.53
17	1	− 0.68	+0.41	+ 0.05	−0.41	+0.41	−0.11	−0.26	+0.41
19	1	− 0.09	+0.45	− 0.56	+0.45	−0.19	−0.11	+0.36	−0.45
23	5	− 0.52	+1.24	− 1.58	+1.24	−0.53	−0.32	+0.98	−1.24
25	7	− 1.58	+0.96	+ 0.11	−0.96	+0.90	−0.24	−0.55	+0.96
Totals		26.70	28.15	16.39	0.31	5.79	6.42	4.55	0.31

For each coil span the number of turns of the winding is changed to keep a constant fundamental flux density.

Table applies to case of 24 stator slots. 18 rotor slots, 2 poles, 3 phase.

maximum of the fundamental. The significance of this point will be seen later.

In general there will be more than one coil per phase belt in the stator and the coils will not be full pitch, both factors having an effect on the relations found for a single coil. In the case of the example previously used having four coils per phase belt it is found that the vector addition of the harmonic components of all four coils gives phase relations as shown in figure 3. Some harmonics are now found to be reversed and others remain as they were for a single coil. The process of finding which ones reverse is discussed in more detail in appendix *B*.

Proceeding to the case of chorded windings, it is found for the sample motor that the various harmonics again either reverse or hold their positions depending on the coil throw as discussed in appendix *B*. For any given stator winding, therefore, it is possible to draw the relation between the fundamental and any or all harmonics for a particular instant.

Considering the rotor for a moment we see that it is equivalent to a winding with one coil per phase belt and so can be represented by figure 2 for any one component of current.

5. The Torque Cycle for Any Harmonic

The next step in the analysis is to place the rotor and stator fundamental waves together with about the same phase relation that they might be expected to have normally with the rotor locked. This would be nearly 180 degrees apart, the actual angle depending upon the power factor of the secondary circuit and the ratio between magnetizing current and total current. For our present purpose the exact angle is not very important and so for simplicity the two fundamental waves will be drawn 180 degrees apart (figure 4*a*). The zero points of the stator wave pass through the center of a phase belt and the zero points of the rotor wave pass through the center of two bars, a pole pitch apart. Under these conditions the 17th harmonic of the stator will bear a fixed relation to the 17th rotor harmonic as shown. An instant later the fundamental waves will have moved slightly in a positive direction while the 17th harmonics will have moved $^1/_{17}$th as far in a negative direction. Thus the picture represents only a particular instant. Since the two 17th waves do not change their positions relative to each other, however, the torque between them, which is zero in this case, is constant.

Suppose now that the rotor be turned through one-quarter of a rotor bar pitch and a new picture be drawn for the same instant in time as before. Figure 4*b* shows this and it will be seen that the two fundamental waves remain in the same relation to one another. This must occur since the secondary current is induced by the primary and the time relation of the current in the bars simply changes to accommodate the new bar position. The 17th stator wave remains as it was but the rotor 17th is shifted relative to the rotor fundamental. The amount of the change can be visualized by going back to figure 4*a* and considering the position of the two rotor waves after the elapse of sufficient time for the fundamental to have moved one-quarter of a rotor bar pitch. This distance is 5 degrees of the fundamental wave or 85 degrees if referred to the harmonic wave length. During this interval the 17th wave will have moved 5 degrees of its own wave length in the opposite direction. The relative movement is thus 90 degrees. A change in rotor position of one-fourth of a bar pitch has therefore resulted in a change in phase relation of the stator and rotor 17th harmonic waves of 90 degrees. In this new position there is a torque exerted between the two fields tending to bring them in line with one another. By continuing the process of shifting the rotor slightly it can be seen that when a shift of one complete bar pitch has been made the relative position of the harmonic fields will have gone through a full cycle and the torque between them will have passed through a set of positive and then negative values.

If the 19th harmonic wave is examined it will be found to have the same properties so that it also produces torque depending on rotor position and goes through a complete cycle as the rotor is moved one rotor tooth pitch. This was one of the requirements of a theory that would agree with the known facts.

We have yet to investigate the effect of other pairs of harmonic fields and it is now proposed to examine the 5th harmonic. The rotor 5th harmonic wave has been shown to be a result of current induced in the rotor bars by the 23d stator harmonic. The relation between the rotor 23d and rotor 5th is shown in figure 5*a*. For the stator it is necessary to select a particular coil throw from which the relation of 23d and 5th can be worked out as shown in appendix *B*. This has been done and is shown in figure 5*b*. Now if the same assumption is made as before and we place the stator and rotor 23d harmonic fields 180 degrees apart, the two 5th harmonic waves fall in the positions shown in figure 5*c*.

The next step is to move the rotor to a new position and see what happens to the two 5th harmonic waves. If we select one-fourth of a rotor slot pitch for the first point as before we reason as follows. The 23d rotor field must bear the same relation to the 23d stator field in all positions of the

rotor since it is induced by it. The rotor must therefore be pictured as it would be after the lapse of sufficient time for the 23d harmonic to move one-fourth of a rotor bar pitch which is 5 fundamental electrical degrees or 115 degrees based on the 23d harmonic wave length. But during this period the rotor 5th harmonic would have moved 115 degrees of its own wave length since all waves move equal parts of their wave lengths in a given time. Converting both distances to degrees of the 5th harmonic wave and noting that both waves move in a negative direction the relative movement of the 5th with respect to the 23d and hence with respect to the stator 5th is,

$$115-115\times5/23=90 \text{ degrees} \qquad (4)$$

Here again we find that the 5th harmonic waves behave in the same manner as the 17th and 19th in that displacement of the rotor causes them to move apart and thus produce torque and the torque cycle requires a displacement of one full rotor bar pitch for its completion. In fact all harmonic pairs that exist follow this same rule.

This establishes a series of torque cycles, each arising from a particular harmonic pair and all existing simultaneously and having the same dependence on rotor position over a slot pitch. Two questions then remain to be answered. First, what are the magnitudes of the various torques? Second, what about the phase relations between the several torque cycles?

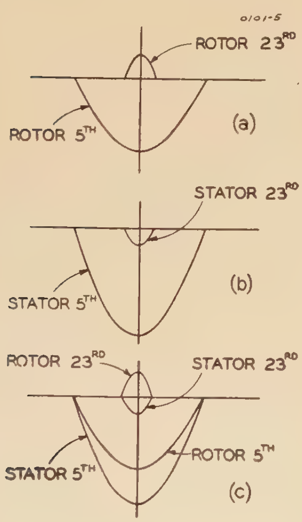

Figure 5

(a)—Relation of rotor 5th and rotor 23d

(b)—Relation of stator 5th and stator 23d for a particular winding

(c)—Relation of stator and rotor 5th-harmonic waves when the rotor 23d is induced by the stator 23d

Note: Waves are not drawn to scale

In answer to the first question, table II has been prepared from calculations on a particular motor by using the torque formula developed in appendix *C*.

The second question, that of phase relation of the torque cycles, is important and is responsible for some of the anomalous results that have been observed. It will be considered in detail in the following section.

6. Relation Between the Various Torque Components

It is evident that there are two possible relations between the rotor and stator waves of a given harmonic when the rotor is in the position shown in figure 4*a*. The two waves are either in phase or 180 degrees out of phase. If they are in phase any movement of the rotor shifts their relative positions in such a way that the resulting torque tends to return the rotor to its original position. This, then, is a stable zero position. On the other hand if the rotor and stator fields are in direct opposition, movement of the rotor shifts the rotor field so as to produce torque assisting the rotor movement. In this case the original position is an unstable zero point.

Since all torque cycles repeat in the same space angle, they either add or subtract and all that remains to be done is to note whether the rotor and stator waves are in phase or out of phase for each harmonic in the original position. As noted above certain harmonics will be found to be one way and others the opposite way for any given winding. Table II has been arranged to show these relations for a specific case. The important fact brought out by this table is the way in which the coil span affects the final results. Thus for a given number of rotor and stator slots and phases there is a wide variation in the locking torque depending on the coil span used. This variation is partly due to the change in magnitude of certain harmonics but the more important cause is the cancellation of forces as a consequence of their phase positions.

Test Results

In order to confirm the theory developed here a two-pole motor having 24 stator slots and 18 rotor slots was wound successively with four sets of coils, each having a different coil span. The number of turns and the operating voltage were adjusted so that the fundamental flux density was the same in all cases. A test of the locked torque variation was made for each winding with two different rotors.

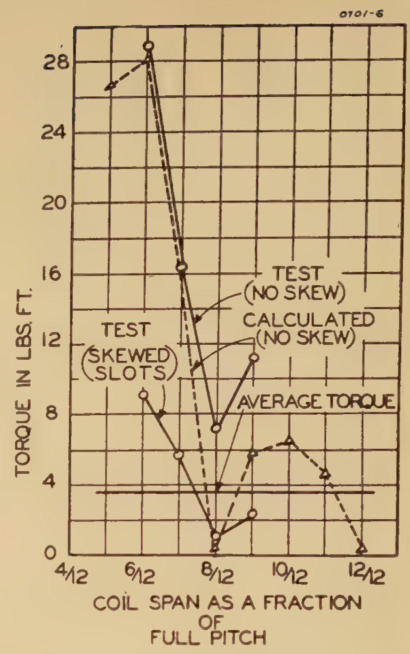

Figure 6. Amplitude of locked-rotor torque variation as affected by coil span. (The total spread between maximum and minimum torque is twice the amplitude shown here)

Curves apply to three-phase motors with 24 stator and 18 rotor slots per pair of poles

One rotor had no skew while the other was skewed a full rotor-slot pitch. The readings were taken at half rated voltage to avoid abnormal heating and consequent changes of resistance.

A sample set of test readings is plotted in figure 1 showing the torque variation as the rotor is moved through a rotor-slot pitch. A minor variation in current occurs also and a curve showing this is included. In figure 6 the amplitude of the torque variation for each of the tests has been replotted to show the effect of a change of coil span. A line showing the average value of the locked torque is included to emphasize the enormous variation that occurs with certain coil spans.

The calculated curve which is shown was worked out in accordance with appendix *C* and applies to the case of the straight-slot rotor. The agreement between test and calculated values, while not as close at all points as might be possible had more rigorous methods been used, seems to indicate that the analysis is essentially correct.

A number of such calculated curves have been worked out for other slot ratios and checked against available data from test files. In most cases fairly satisfactory agreement has been found. The effect of skew has not been calculated in detail but approximate methods of taking it into account can be devised.

In the interest of accuracy it should be

recorded that some of the tests, particularly those with no skew, showed an additional variation having a cycle of one-fourth of a rotor-slot pitch. No attempt has been made to account for this component of the torque variation but it is probable that accurate plots of the air gap flux would reveal the cause. Figure 8 shows this type of variation.

The calculated curve of figure 6 is applicable to any motor having the same number of slots per pair of poles as those used for this example provided the torque scale is adjusted to suit the particular values of current as set forth in appendix *C*. For all other three-phase slot combinations which have been investigated so far the general shape of the curve is similar, having minimum points at full pitch and two-thirds pitch.

It may be argued that once the causes

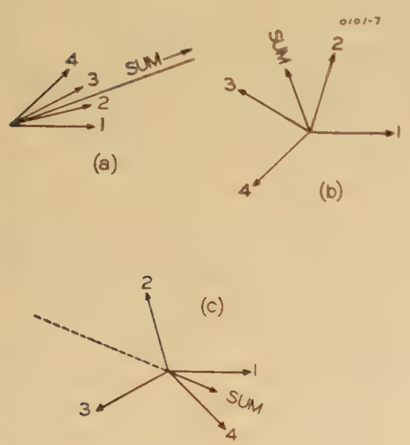

Figure 7

(*a*)—Summation of four fundamental vectors

(*b*)—Summation of four fifth-harmonic vectors

(*c*)—Summation of four seventh-harmonic vectors

of dead points are understood there should be little need to calculate their effects accurately since most designers will simply avoid slot numbers that produce them. The fact remains that other considerations may sometimes determine the slot numbers and thus a means of finding the best coil span is useful.

Rules to Avoid Dead Points

Since there must be stator and rotor harmonics of the same order traveling in the same direction to produce dead points, trouble can be avoided in the case of integral-slot windings by choosing a number of rotor slots which is not a multiple of the number of stator phase belts. For fractional-slot windings of the balanced type the rule is as follows: Avoid a number of rotor slots which is a multiple of the number of phase belts divided by Y, where Y is the denominator of the fraction, reduced to its lowest terms, expressing the number of stator slots per pole per phase.

If, for any reason, it is desirable to use one of these vulnerable slot ratios a coil span should be used that will minimize the dead-point effect.

A skewed rotor will always decrease the dead-point effect.

Previous Work

After the present study had been completed it was found that the idea of positive and negative signs for the torque components was not original but had been developed independently by Dreyfus[1] in Sweden. It was used later by Richter[2] in Germany and included in his "Elektrische Maschinen." Unfortunately there appears to be no English translation of either Dreyfus' paper or Richter's books and so their results have not had the appreciation in this country that they deserve.

A German investigator, Möller,[3] has taken a series of tests with various slot combinations. His tests showed strong locking with most of the combinations having a slot difference which is a multiple of the phase belts but he also got a weak locking torque in cases where the difference was a multiple of half the phase belts. The latter he attributes to a possible second harmonic of the slot pulsation. The coil span of the stator coils is not stated and no indication is given that its effect was considered important.

Gray[4] discusses the question of dead points and attributes the cause to permeance variations entirely. He shows a test on one motor in which most of the torque variation has a space distribution corresponding to a fifth harmonic of the rotor slot pitch. His motor has five stator slots for each four rotor slots but the numbers of poles, phases, and total slots are not given.

A discussion by Cotton[5] points to permeance variations as the principal cause and states that a common factor for slot numbers is to be avoided. Say and Pink[6] state that locking at standstill occurs when the stator and rotor slots are the same in number or if one is a multiple of the other.

The most recent reference to the subject before the AIEE occurred during the discussion of E.E. Dreese's[7] 1930 paper on synchronous running torques.

Appendix A. Magnitude of the Harmonic Fields

1. Stator

The magnitude of the stator harmonic fields which arise from the distribution of the winding can be calculated with fair accuracy by assuming that the slot current is concentrated at the center line of each slot and that the permeance is uniform. With these assumptions,

$$B_{Sn}=\frac{k_n}{nk_1} \tag{5}$$

where

B_{Sn} = maximum value of nth harmonic field in terms of the fundamental field.

k_1 and k_n = product of pitch and distribution factors for fundamental and nth harmonic.

2. Rotor Fields

The magnitudes of the mth harmonics, or incidental fields of the rotor bear a fixed relation to the nth harmonic fields. The well-known relationship between the harmonic components of a rectangular wave is that the magnitude of each component is proportional to the reciprocal of its harmonic order. For two fields of orders n and m resulting from one set of currents the relation between them is,

$$B_{Rm}=\frac{nB_{Rn}}{m} \tag{6}$$

where B_{Rm} and B_{Rn} are the magnitudes of the rotor mth and nth fields respectively. The problem then is first to find the value of B_{Rn}. One simple, approximate solution that suggests itself is to assume the rotor

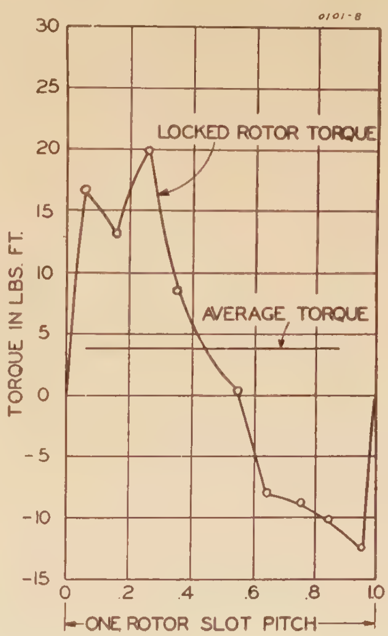

Figure 8. Typical test curve showing variation of locked-rotor torque with rotor position for motor without skewed slots

Motor had 24 stator slots, 18 rotor slots, 2 poles, 3 phases, 7/12 coil span

ampere turns equal the stator ampere turns. For the fundamental field or for some of the lower order harmonics this might be done without serious error, but when applied to cases where n is high and m is low it is soon apparent that this simple relationship is far from the truth. The reason for this is that the incidental mth harmonic fields produce flux linkages with the rotor bars which, in the case of a high ratio of n to m, become the determining factors in limiting the rotor current. A more nearly accurate method of finding the value of the rotor fields, though still an approximation, is to equate the rotor bar voltage set up by the stator nth field to the sum of the voltages due to the rotor nth and mth fields.

Thus,

$$E_{Sn}=E_{Rn}+E_{Rm1}+E_{Rm2}+\ldots \tag{7}$$

where,

E_{Sn} = rotor bar voltage induced by stator nth harmonic.

E_{Rn} = rotor bar voltage induced by rotor nth harmonic.

E_{Rm1} = rotor bar voltage induced by rotor m_1th harmonic.

E_{Rm2} = rotor bar voltage induced by rotor m_2th harmonic.

If we use B with its proper subscript to represent the maximum flux density of the various fields then, using per-unit notation,

$$E_{Sn}=B_{Sn} \tag{8}$$

$$E_{Rn}=B_{Rn} \tag{9}$$

$$E_{Rm1}=\frac{nB_{Rm1}}{m} \tag{10}$$

$$E_{Rm2}=\frac{nB_{Rm2}}{m} \tag{11}$$

which states that the voltages due to the nth fields are proportional to the magnitudes of those fields but that the voltage due to an mth field is n/m times the value of the mth field since the latter has a different space distribution. We noted before that:

$$B_{Rm}=\frac{nB_{Rn}}{m} \tag{6}$$

Thus we may write,

$$B_{Sn}=B_{Rn}+\left(\frac{n}{m_1}\right)^2 B_{Rn}+\left(\frac{n}{m_2}\right)^2 B_{Rn}+\ldots \tag{12}$$

and,

$$B_{Rn}=\frac{B_{Sn}}{1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2} \tag{13}$$

The mth rotor fields are:

$$B_{Rm1}=\frac{n/m_1\, B_{Sn}}{1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2} \tag{14}$$

and,

$$B_{Rm2}=\frac{n/m_2 B_{Sn}}{1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2} \tag{15}$$

Expressed in terms of the fundamental stator field density, and the pitch and distribution factors, the rotor mth fields are,

$$B_{Rm1}=\frac{Kn}{m_1\,{}_1\left[1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2\right]} \tag{16}$$

$$B_{Rm2}=\frac{Kn}{m_2k_1\left[1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2\right]} \tag{17}$$

Appendix B. Phase Relation Between the Harmonic Fields

If the fundamental fields due to each of the coils of a phase belt are added together the vector relations are shown in figure 7*a*. The vector representing the resultant field for the group lies at the center of the group of individual vectors.

A similar vector addition for the fifth harmonic fields of the phase group is shown in figure 7*b*. The angle between vectors is now five times the angle between fundamental vectors. Here again the resultant is located midway between the second and third vectors.

Figure 7*c* shows the addition of vectors for the seventh harmonic fields but this time the resultant vector is negative and therefore lies 180 degrees from the dotted line representing the center of the group.

Continuing with the other harmonic fields it is found that some have a positive resultant located along the center of the group while with others the resultant is negative. Thus with respect to the resultant fundamental field certain of the harmonic fields maintain the same phase relation that existed for a single coil while for others the effect of grouping a number of coils together in a phase belt is to reverse the phase relation of fundamental and harmonic. The term phase relation is used here to indicate whether at the point of positive maximum of the fundamental the given harmonic has a positive or a negative value. To find whether a given harmonic will reverse its position for a group of coils as compared to a single full-pitch coil it is only necessary to solve the expression for the sum of a group of vectors separated by a uniform angle and note the algebraic sign. If Σ is the resultant vector,

$$\Sigma=\frac{\sin Nn\dfrac{\alpha}{2}}{\sin n\dfrac{\alpha}{2}} \tag{18}$$

where N is the number of vectors and $n\alpha$ is the angle between them. When Σ is positive the harmonic under consideration keeps the same relation to the fundamental that it has when a single coil is examined. If the sign is negative the harmonic reverses.

By a similar process the effect of chording the winding may be investigated. In this case the top and bottom layers of the winding are considered as two groups of coils displaced in phase by the angle by which the coil span differs from full pitch. The expression for Σ is solved for the case of two vectors differing by n times this angle and the algebraic signs determine whether or not the nth harmonic is reversed due to chording.

These relationships can be kept clear by using positive and negative signs for the distribution or breadth factor and for the chord or pitch factor. Thus the factor Kn in appendix A which is the product of these two factors will be either positive or negative. The torque formula in appendix C will also give either positive or negative results depending upon the algebraic signs of Kn and Km. Table II shows the torque components with their algebraic signs for a typical motor with various coil spans.

Appendix C. The Torque Formula

The torque developed between stator and rotor fields of the same harmonic order varies with the phase relation between them, reaching a maximum at 90 degrees. The maximum torque is proportional to the product of the magnitudes of the two fields. When dealing with several harmonics it must be kept in mind that for the same maximum flux densities the torques of various pairs of fields are also proportional to the harmonic orders. From these elementary considerations we may write:

$$\text{Torque} \propto m\times B_{Rm}\times B_{Sm} \tag{19}$$

for any one particular harmonic. Substituting the expressions for stator and rotor fields and including a proportionality factor the torque in per unit terms is,

$$\text{Torque}=\frac{K_nK_m\ I_L^2}{mK_1^2\left[1+\left(\frac{n}{m_1}\right)^2+\left(\frac{n}{m_2}\right)^2\right]I_1I_m\sin\theta} \tag{20}$$

where,

I_L = locked current

I_1 = rated current

I_m = magnetizing current

θ = phase angle between I_1 and I_m

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Transactions

Preprint of Technical Papers Comprising Pages 643–89 of the 1940 Volume

A Decade of Progress in the Use of Electronic Tubes

Part I—In the Field of Communication*

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THE dependency of the art of communication on the science of electronics is so great as to make a review of progress in electronics almost of necessity a review of the field of communications itself. While it is true that the early forms of telephone and radio communication advanced to a degree without the use of electronic devices as we know them today, the recognition of the vacuum tube as an amplifier and generator of high-frequency alternating currents in the years just preceding the first World War marked a turning point in the development of the communication art. From that day to this the progress of electronics and communications has gone hand in hand. The need of the communications engineer for new electronic tools has kept him continually urging the electronics engineer to improve old devices and to originate new ones, and each time the efforts of the latter have been rewarded with success, the fruits of his work have been immediately applied to produce new and more startling miracles of long-distance communication.

Because of the close relationship of electronics and communications it is necessary in reviewing the progress of the last decade to keep in mind that it is progress in electronics and not in communications which is our theme. It will be necessary to survey the trends in communications during the period under review, but then it will be necessary to ask to what extent the progress which has been made is due to advances in the electronic field and what advances in the electronic devices themselves have laid the foundation of this progress. There has been no attempt made to make this review comprehensive in the sense that it include all items of progress which are of individual interest. To do so would make it merely a catalog of these many advances and an index to the periodical literature of the subject. Rather the object has been to trace the most significant trends of development in the various fields and to emphasize those lines of advance which appear to be most closely related to the general direction of progress in the several fields of electrical communication.

The Trend in Radio—to Ultrashort Waves

The history of radio has seen a continual demand for expansion of the usable region of the frequency spectrum. Because the number of available communication channels is limited it has been necessary to ration the frequency spectrum by governmental regulation and international agreement among the various users and classes of service. Existing services, most of which are experiencing a continual expansion, have completely absorbed the allocations in the intermediate and short-wave band and leave nowhere to place new services but in the ultrashort-wave region above 30 megacycles. Not only are the new services forced to the ultrahigh frequencies by congestion at the longer waves, but in some cases they are themselves of such a nature that an adequate number of channels with the necessary band width can be obtained only at the high frequencies. Television and wide-band frequency modulation are cases in point. A band width of over four megacycles is required to transmit a modern high definition television image. Frequency-modulation systems at present proposed require a 150-kilocycle band. Radio relay systems for these same services will require band widths at least as great and can obviously be accommodated only in the ultrashort-wave region. The development of these and other wide-band services is therefore dependent on satisfactory means for working at ultrahigh frequencies.

Another reason for the current interest in ultrashort waves is that new services are developing making use of their unique transmission properties. Their very shortness makes practical the construction of directive antenna systems and this can be more easily accomplished the shorter the waves. Directivity, which of course can be applied only in the case of point-to-point services, greatly reduces the power requirements on the transmitter. For broadcast services the problem of interference between stations is simplified because the transmission of ultrashort waves is approximately limited to line-of-sight paths. To relate their propagation exactly to line of sight as has been frequently done in recent years is an oversimplification of the problem but it is probably true that the ultrashort waves will find few applications for ranges beyond 100 miles and that interference need not be feared beyond a few hundred miles at most.

In the very front of this field, in the range of centimeter waves, that is above 300 megacycles, the directive possibilities of ultrashort-wave systems become particularly marked. Commercial applications in this region are as yet few, but may be expected to increase rapidly in the future. As examples of the unique type of problem capable of solution only by the use of centimeter-wave technique may be cited the development of the absolute altimeter to measure the height of an airplane over the terrain by the reflection of radio waves[6] and a 40-centimeter airplane blind-landing system.[7]

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* A report prepared for the AIEE joint subcommittee on electronics: H. M. Turner, *chairman;* W. R. Brownlee, J. H. Cox, J. W. Dawson, T. F. Gray, S. B. Ingram, D. C. Prince, Joseph Slepian, Thomas Spooner, W. C. White, and T. A. Worcester. Part II appears on succeeding pages.

1. For all numbered references, see list at end of paper.

The Trend in Television—to Electronic Television

Television is an art which has developed almost entirely within the last 15 years. In no field is the close relationship between communications and electronics better illustrated than here. All modern systems of television depend on the modulation of a carrier frequency wave by a video signal. This video signal is derived by scanning the picture in a series of horizontal lines, the amplitude of the video signal varying with the brightness of the individual picture element traversed by the scanning beam. The transmission of the modulated carrier is a radio problem in which the principal difficulties to be overcome are those related to the wide band required for a high-definition picture and to the high frequencies assigned for television transmission. At the receiver, demodulation and a second scanning process synchronized with the first are required to reconstruct the picture. The earlier systems of television used mechanical scanning methods at both transmitter and receiver. These mechanical scanning methods had numerous disadvantages. They called for rapidly rotating mechanical elements, perforated disks, lens disks, drums bearing mirrors, and numerous other devices of a mechano-optical nature. It is inherently more difficult to synchronize two rapidly rotating mechanical systems than two electrical circuits on account of the inertia of the mechanical parts. It was hard to get sufficient optical efficiency either for satisfactory studio technique at the transmitter or a sufficiently bright image at the receiver. All these difficulties were magnified when the progress of the art called for the production of a high-definition picture, the mechanical problems because a higher scanning speed was required, the optical difficulties because the light available was proportional to the area of the scanning spot and high definition meant a smaller spot. A solution was sought in electronic television. It was found first at the receiver, for the cathode-ray tube which had been used for some time as a laboratory tool had all the elements of an electronic scanning device for a television receiver and needed only to be adapted and improved for the purpose. For the transmitter, however, completely new devices had to be invented and they came in the form of the Iconoscope, the image dissector, and later modifications of these. Today electronic methods of scanning have replaced mechanical methods practically universally at the transmitter although it is as yet too early to say that some place may not be retained for mechanical systems, for example in the scanning of film. At the receiver electronic methods are also most generally used, the Scophony system[51] being the outstanding example of a mechanical scanning method still successfully holding a place for itself.

The Trend in Telephony—to Broad-Band Carrier Systems

Electronic devices have played a major part in the field of long-distance telephone transmission for many years. In local circuits the attenuation is small enough so that no amplification between the transmitter and receiver is necessary to counteract it, but in all long-distance circuits attenuations are so great that without the vacuum-tube amplifier, or telephone repeater as it is called, communication would be impossible. The earlier systems were voice-frequency systems in which one pair of conductors was used to carry each conversation. The advantages of carrier systems in which one pair of conductors could carry several frequency channels each modulated with its own voice current were early recognized. Such systems generally carrying three speech channels have been in use for 20 years or more. The total frequency band transmitted in these earlier systems was however limited to about 24 kilocycles. Within the last decade tremendous impetus has been given to the development of broad-band carrier systems where the frequency band transmitted may be as high as several thousand kilocycles.

There are two general types of broad band carrier systems.[8–10] There are those in which, by the addition of repeaters and terminal equipment, the carrying capacity of existing conductors both cable and open wire can be greatly increased.[11–14] These systems in general will accommodate from 12 to 16 channels per pair and utilize carrier frequencies up to 145 kilocycles. They are extremely important from an economic standpoint since they permit great economy in the amount of plant required to accommodate an increase in traffic when existing facilities are fully utilized. Then there are the very broad-band coaxial-conductor systems.[15,16] The circuit in this case consists of two concentric conductors separated by small dielectric spacers. Such systems are capable of transmitting exceedingly high frequencies with a maximum degree of shielding from outside interference. Their importance lies not only in their ability to transmit as many as several hundred telephone conversations simultaneously, but also in the fact that they present the only practical means at present in prospect for setting up wire transmission systems capable of transmitting high definition images in television broadcasting networks.[17] The detailed discussion of broad-band carrier systems is outside the scope of this paper. What does concern us here is the problem of amplification which must be accomplished by electronic means. In the cable carrier system attenuations run as high as 4 decibels per mile, in the coaxial system 8 decibels at two megacycles. If we envision 1,000 miles of coaxial circuit the attenuation which has to be compensated by amplification amounts to 8,000 decibels. This represents a total power amplification between terminals of 10^{800}. The requirements on the amplifiers of such a system are obviously very stringent. They must have a high degree of stability so that the power level at the terminals shall be constant, they must be linear so that the intermodulation products which would produce interference with one voice channel by another shall be negligible, and they must be capable of transmitting a wide band of frequencies. Such requirements can be met only by the stabilized-feed-back amplifier[74] which is an electronic circuit development of the highest order of importance. Without this solution of the amplifier problem broad-band carrier systems as we know them today would be impractical.

While considering carrier telephone systems we should pause to note one of the losses of electronics as a contender for supremacy in the telephone transmission field. Copper-oxide modulators and demodulators have in general proved superior from the standpoint of compactness, economy, and ease of maintenance to the vacuum-tube circuits formerly used for this purpose.[18]

Progress in Electronic Devices

So far consideration has been given to the trend of progress in the several major divisions of the communications field and it has been shown how electronics has played an important role in contributing to this progress. The remainder of the paper will be devoted to a review of progress more specifically in the electronic devices themselves. In considering these it will be convenient to divide the devices into several broad classes: those depending primarily on thermionic emission

for their operation, those depending on secondary and photoelectric emission and the new science of electron optics, and those based on the phenomena of gas discharges. Finally a few of the most fundamental electronic circuit developments will be described.

Thermionic Devices

The extension of radio into the ultrahigh-frequency portion of the spectrum has been paralleled by a corresponding growth of interest in the development of vacuum-tube devices for use at these frequencies. Those which have found most general use up to the present time are modifications of the familiar three-element or negative-grid vacuum tube designed particularly to fill the requirements of ultrahigh-frequency operation.[19–21] Major development efforts have proceeded in two directions; toward the generation of relatively small amounts of radio-frequency power at higher and higher frequencies, attempting to extend the useful portion of the radio spectrum into the region of the centimeter waves, and toward an increase in the usable range of power at more moderate frequencies in the lower parts of the ultrashort-wave region where television and frequency modulation have brought a commercial demand for radio transmitters. In the former class the frequency limit has been pushed up to 1,800 megacycles; in the latter water-cooled power amplifiers capable of power outputs of approximately 10 kw at 100 megacycles are now commercially available.

The tendency of negative-grid tubes to produce unwanted oscillations due to the feedback of power from the output to the input circuits makes the problem of producing amplifiers at the ultrahigh frequencies more difficult than that of producing satisfactory oscillators. Methods of neutralization which can be used at lower frequencies to prevent these oscillations from occurring become inadequate at the higher frequencies because of the inherent difficulties of circuit technique. The problem has been solved by the construction of special push-pull pentodes containing two tube structures within one envelope.[22,23] With such tubes, stable amplifiers with power outputs of 10 watts at 250 megacycles and some measurable amplification as high as 500 megacycles have been constructed.

Negative-grid tubes are used both as oscillators and amplifiers. Two other devices, both by their nature incapable of amplification but interesting as oscillators because their power-generating capacity exceeds that of negative-grid tubes in the centimeter-wave region, have received considerable attention.[24–26] These are the positive-grid or Barkhausen oscillator and the magnetron. Of these the latter has received the greater attention. Magnetrons depend for their operation on the curvature of the path of the electrons as they move under the influence of the electrostatic field between a filament and a surrounding cylindrical anode placed in a homogeneous magnetic field along the axis. Two general modes of oscillation exist. In the first the static negative-resistance characteristic of the tube is utilized. Operating in this mode magnetrons have been used to produce power outputs of as high as 450 watts at 46 centimeters.[27,28] Efficiencies in the range from 30 to 60 per cent have been reported. While this is considerably better than has been obtained with the negative-grid triode, there are difficulties of frequency stability and modulation with magnetrons, and these together with the additional complication of the equipment required to supply the magnetic field make them rather poor competitors of negative-grid tubes at these frequencies. The second type of magnetron oscillation is one in which the transit time of the electrons is approximately equal to the period of the radio-frequency output.[29] Operating in this manner the magnetron has established the record for ultrahigh-frequency wave generation at 61,000 megacycles corresponding to a wave length of only 4.9 millimeters.[30]

For the conventional negative-grid triode the maximum power-handling capacity has been shown to vary inversely as the square of the maximum frequency at which the tube is designed to operate[19] so that some new principle must be called into play if significantly greater power outputs are to be realized in the centimeter-wave region. Very recently tubes operating on such fundamentally new principles have occupied a great deal of attention by research workers and show promise of giving performance considerably better than that yielded by negative-grid tubes both with respect to power output in the centimeter-wave region and to their maximum frequency of operation. They differ in their principles from conventional tubes in that the radio-frequency output is taken from the electron stream by induction in an anode element which is not the same as that which collects the current and which therefore does not need to dissipate the d-c power. The variations in electron density capable of inducing these radio-frequency currents are produced in two different ways. In the inductive output tube[31] the conduction current is modulated by a cathode grid structure exactly as in the ordinary triode. In the "velocity modulation" tube[32] or in the so-called "klystron"[33] the principle of velocity variation is used. A stream of electrons accelerated from a cathode passes through two grids between which a radio-frequency signal is applied. This signal retards or accelerates the electrons according to the phase of the cycle at which they happen to pass the grid giving rise to velocity variation of the beam which then passes through a field-free "drift space" in which the faster electrons catch up to the slower ones. A bunching or conduction current variation of the beam is thus produced and renders it capable of generating radio-frequency currents in the output electrodes by induction. Tubes of this design overcome two limitations inherent in the negative-grid type. Higher efficiencies may be attained because the output electrode is not called upon to dissipate the tube losses and in the case of velocity-variation tubes transit time through the radio-frequency input section of the device is much less than in triodes since the electrons are moving with high velocity when they enter this space instead of having to accelerate from zero velocity. This greatly reduces "active grid loss", that is, the increase of grid driving power required as the operating frequency is increased which is directly due to the transit time becoming comparable in magnitude with the radio-frequency period and which is the fundamental limiting factor in the high-frequency operation of negative grid tubes. In contrast to the magnetron, velocity-variation tubes are well suited to operation as radio-frequency amplifiers. Experimental data on performance reported in the literature are meager as yet but operation at frequencies as high as 6,000 megacycles (five centimeters) and oscillator power outputs of 500 watts at 750 megacycles have been reported.[1]

Space will not permit the mention of many detailed improvements in the general field of thermionic vacuum tubes, but some reference should be made to the application of electron optics to thermionic devices in the beam power tube.[38] In this tube the electron stream, which is confined to move in beams by accurately lined up grids and by electrostatic deflecting plates, produces a space-charge potential minimum in the neighborhood of the plate which suppresses secondary emission just as the retarding field of the suppressor grid does in the ordinary pentode. Such tubes have re-

ceived wide acceptance as power amplifiers on account of the high efficiency obtainable with them.

Wide-band amplifiers of the type required in television receivers and in broad-band carrier systems require tubes with a high ratio of transconductance to interelectrode capacitance. Recently developed tubes for these systems have shown considerable advances in this respect[39,40] and in view of the increasing importance of broad band systems, further advances can be anticipated along this line.

Devices Based on Secondary Emission, Photoelectric Emission, and Electron Optics

The devices which we will consider in this section are largely a group whose development has been brought about by the needs of the new art of electronic television. They have been made possible by the great advances made in the underlying science of electron optics, and by putting to work the phenomenon of secondary emission. The knowledge and application of the laws of electron optics have progressed to the point where beams of electrons can be focused and directed in accord with well-defined and well-understood laws. Electron images can be projected in space by electron lenses which consist of electric fields set up by suitably disposed electrodes at the proper electrical potentials or by magnetic fields from the appropriate current-carrying coils.

The basic phenomena of secondary emission have been known for many years. Their effect in modifying the characteristics of vacuum tubes was also well known, the third grid in the ordinary pentode being introduced specifically for the purpose of suppressing secondary electron emission from the plate. It was not however until recently that it was demonstrated that since one electron impinging on a suitable surface with appropriate energy has the ability to release more than one secondary electron, it is possible to build electronic amplifying devices based on the phenomenon of secondary emission. These devices are called secondary emission multipliers.[41,42,67] In general they consist of a number of successive electrodes whose surfaces have been suitably treated to give them a high secondary emission ratio and which are maintained at sufficient potential difference to give an optimum over-all multiplication to the device. If under these conditions a secondary emission ratio of m prevails, the multiplication in k stages is m^k. Values of secondary emission ratio in present-day multipliers are typically in the neighborhood of four and the number of stages varies up to 16. Total over-all amplifications of several billion have been reported.[43] The limiting output is determined by power dissipation in the last stage and defocusing of the electron beam due to space charge. Multipliers can be associated with various types of input. When applied to a tube with a photoelectric input, multipliers can readily be produced with sensitivities as great as 30 milliamperes per lumen or greater.[44]

One advantage of such multipliers over the combination of a photoelectric cell and a thermionic amplifier is that no coupling resistor is required between the photoelectric-cell output and the first stage of amplification. Thermal noise in this resistor is therefore eliminated, and for this reason the photoelectric multiplier is capable of operating at much lower levels of illumination than the photoelectric cell with thermionic amplification.[41,45] As described below, multipliers can be associated directly with the output of television pickup devices. Finally, secondary-emission multiplication applied to the output of an ordinary thermionic vacuum tube offers attractive possibilities in the field of wide-band amplification since circuit problems could be greatly simplified if an amplifying device were available capable of giving a greatly increased gain per stage. The multiplier can do this and has the further important property that its amplification is essentially independent of frequency up to many megacycles where transit time becomes a limiting factor. One interesting commercial tube in which one stage of secondary electron multiplication is added to an ordinary tetrode, has a transconductance of 14,000 micromhos.[46]

The electron optical problems of multiplier design are worthy of special attention because of the ingenious methods which have been devised for their solution. Earlier multipliers used magnetic focusing to assure that all the electrons originating on one stage were suitably collected on the succeeding one. Present-day multipliers are generally of the electrostatic type, the electrodes being so shaped that the equivalent focusing action is obtained. The problem of determining electron trajectories in ordinary multiplier structures is too complex to admit of ready mathematical solution. Electrolytic tank models for determining electric fields in complicated structures and mechanical models for determining electron trajectories have proved invaluable design tools.[43,44] In the latter method metal spheres rolling on a stretched rubber membrane whose slope simulates the electric fields of the tube elements can be shown to trace out the trajectories with a highly practical degree of accuracy.

In electronic television systems four types of pickup tubes are today in common use. The first is the image dissector.[55–8] In this tube the visual image is focused on a photoelectric surface. The photoelectrons emitted are focused by means of an axial magnetic field in the plane of the scanning aperture. This whole image is then moved back and forth across this stationary scanning aperture, the image thus being "dissected." Since the aperture must be minute for a high-definition television picture, the current is very small and passes immediately into an electrostatic electron multiplier for amplification. The output from the last stage of this multiplier is the video signal.

The second pickup tube is the Iconoscope.[56,59–64] The essential element of this tube is the mosaic plate consisting of minute islands of photoemissive substance backed by a thin insulating layer of mica the reverse side of which is covered with a conducting coating. This layer forms the output electrode of the device and to it the elements of the mosaic are capacitively coupled. The optical image is focused on the mosaic. Photoelectrons are emitted from the elements causing them to assume a potential which is dependent on the intensity of the light falling upon them. The mosaic is scanned by an electron beam from an electron gun. This electron beam impinging on the surface under conditions in which the secondary emission ratio is greater than one recharges the element to a definite equilibrium potential and the variations in the recharging current required constitute the video signal which is transmitted to the output circuit through the capacity of the mosaic.

The Iconoscope has the important advantage over the image dissector that its elements act to store charge during at least a portion of the scanning time and this stored charge is then swept away quickly during the traverse of the scanning beam. This gives it a considerably greater sensitivity than the image dissector and makes it suitable for taking scenes under many conditions of illumination where the image dissector is inadequate. Balanced against this is the presence in the Iconoscope output of a spurious signal or "dark spot" arising from the redistribution of photoelectrons and of secondary electrons from the

scanning spot over the whole mosaic surface. This spurious signal must be balanced out by the electrical insertion of a compensating signal from a special electrical network. The image dissector also has an advantage in being a directly coupled device the output of which contains information as to the general level of illumination of the picture. The Iconoscope being capacitively coupled gives information only as to variations in illumination, and its output must therefore be continuously monitored to adjust for changes in background illumination as well as for the dark-spot signal just mentioned. At present the Iconoscope type of camera appears to have most general applicability on account of its greater sensitivity but the simplicity of operation of the image dissector gives it a field of use in special cases, for example in pickup from motion-picture film where adequate levels of illumination are easily obtained.

Sensitive as the Iconoscope is on account of its charge-storing property, still more sensitive pickup devices are urgently required by television techniques. Tests show that the charge storage in the mosaic is not greater than five or ten per cent what would be expected under ideal charge-storage conditions, being low because the field which attracts the photoelectrons from the mosaic is small and because only a fraction of the secondary emission current reaches the anode. The super-emitron[64] or its American counterpart the image Iconoscope[65] increase this low efficiency. In these tubes the photoelectric surface is separated from the mosaic, an electron image of the electrons emanating from the former being focused on the latter by means of an electron lens. This mosaic is then scanned as in the Iconoscope. This arrangement enables two gains to be made. A more efficient photoemissive surface can be produced and the photoelectrons may be drawn away from it under conditions of voltage saturation. An over-all gain in sensitivity of about ten times over the Iconoscope has been achieved in practical tubes of this type. They are used to some extent in commercial television pickups particularly under low outdoor conditions of illumination.

Another interesting pickup tube, the "orthicon," has recently been described.[66] It differs from the Iconoscope in that the mosaic is scanned by a beam of low velocity electrons. The photoelectrons leave the surface under voltage saturation conditions giving the tube an over-all high efficiency and making the light response linear. Since the energy of the scanning electrons is low, secondary emission plays little or no part in the operation of the device and the level of the spurious signal is low. Such devices appear to offer promise but problems of focusing a low-velocity beam are formidable and the definition of pictures produced with such tubes do not at present compare favorably with those obtained with the Iconoscope.

For the picture tube in television receivers the conventional cathode-ray oscilloscope tube needed only to be adapted, although many detailed improvements have been required. Electron guns for producing high-current electron beams of accurate focus have been developed.[68] Great progress has been made in the production and use of fluorescent materials.[69] Much of the current development effort is directed at the production of tubes with a sufficiently bright image to enable optical projection onto a large screen.[70] Tubes for this purpose with electron-beam energies as high as 80 kv are under laboratory investigation.[49]

Gas-Discharge Devices

In communication systems gas-filled tubes have found most general use as rectifiers to provide d-c power from a-c supplies or as relay devices in control and signaling systems. Use in circuits carrying the communication signals themselves has proved impractical because of the noise inherent in the gas discharge itself and various proposals for gas-filled amplifying devices have so far proved impractical on this account.

In radiobroadcast transmitters, mercury-vapor rectifiers have largely replaced rotating machines for providing d-c supplies. Mercury-vapor rectifiers have been found to give efficient service with a minimum of maintenance for all outputs up to 20 kv and 100 amperes.

Thyratrons or gas-filled rectifiers which contain a grid to control the starting of the discharge are also becoming widely used in rectifiers for battery charging in telephone central offices. By utilizing grid control in such tubes, regulated rectifiers can be built which automatically adjust the charging rate of the battery in such a way as to hold its terminal voltage constant as load and line voltages vary.[71,72] This condition makes for long battery life and also eliminates the maintenance required by manually adjusted chargers.

In control and signaling systems one type of gas-filled device, the cold-cathode tube,[73] appears to offer prospect of extensive use. In its simplest form it consists of a gas discharge tube containing a cathode, an anode, and an auxiliary electrode. The passage of a small amount of current of the order of one microampere to this auxiliary electrode will control the starting of the anode current which can then be as large as 10 to 100 milliamperes in existing types. The tube thus functions as an extremely sensitive relay. Dissimilarity of cathode and anode can be used to provide a rectification property. In recent years cold-cathode tubes have been extensively applied in four-party selective-ringing circuits for the selective signaling of telephone subscribers on party lines.

Electronic-Circuit Developments

The importance of the stabilized-feedback amplifier in wide-band carrier telephone systems has been brought out. The principle of such amplifiers is basically very simple.[74] A portion of the output is fed back to the amplifier input usually through an attenuating network in such a manner as exactly to oppose the input signal. This reduces the over-all gain of the amplifier and also reduces noise and distortion usually in the same proportion. With modern high-amplification-constant vacuum tubes the decrease in gain can be readily restored and the net result is an amplifier which is superlatively better than the simple amplifier without feedback. The first major advantage of such amplifiers is the linearity of their characteristics. In carrier systems this is important since intermodulation which causes interference between the various speech channels can be practically eliminated. To obtain this same result without the use of stabilized feedback would require the use of vacuum tubes of much larger power ratings operated over a small portion of their characteristics with a consequently greatly reduced efficiency. The second advantage of the negative-feed-back amplifier is its stability. When the amount of feedback is large it can be shown that the over-all amplification depends only on the characteristics of the feed-back circuit and is practically independent of the amplifying circuit. Since the feed-back circuit contains only fixed circuit elements and no vacuum tubes the over-all amplification becomes independent of variations in tube characteristics and supply voltages. This stability is essential in a carrier system which has many repeaters in tandem if the total amplification between terminals is to remain constant. The third advantage is the ease with which the over-all gain

and the gain frequency characteristic of the amplifier can be controlled. These are functions only of the feedback circuit characteristic which can be given any desired shape by the introduction of appropriately designed equalizing networks. In carrier systems the attenuation-frequency characteristic of the line and the variations in attenuation-frequency characteristic with temperature can thus be almost exactly compensated by adjusting the gain-frequency characteristic of the repeaters.

A great amount of technical interest and commercial activity is currently being devoted to a new form of radio-broadcasting known as wide-band frequency modulation.[75,76] It is as yet too early to say what the ultimate development of this system will be, but its most enthusiastic advocates foresee the obsolescence of the present system operating within the broadcast band in the neighborhood of one megacycle and the development of a new ultrahigh-frequency system operating on the principles of frequency modulation. In conventional radio-telephone systems the amplitude of the carrier wave is modulated by the audio frequency. In the proposed system the frequency of the carrier is caused to vary back and forth over a frequency band approximately 150 kilocycles in width, the instantaneous deviation of the frequency from the mean being proportional to the instantaneous amplitude of the modulating audio signal. This system has several interesting features as compared with the existing low-frequency amplitude-modulation broadcasting. Natural atmospheric noise is inherently low in the ultrahigh-frequency region of the radio spectrum. Interference from automobile ignition systems, on the other hand, is more severe than at broadcast frequencies. The characteristics of the proposed frequency-modulation system are such that the radio-frequency interference-to-signal ratio may be higher without noticeable interference with the program than is the case with amplitude modulation. The same characteristics of the system which make this true are effective in reducing interference between stations on the same frequency. It is possible with frequency modulation to transmit programs of high fidelity without unduly high expenditures of power at the transmitter but this is done at the expense of using a wider frequency channel.

The extension of high-frequency practice to the centimeter wave region has called for new circuit techniques. As the frequency is increased the lumped inductances and capacities of the resonant circuits decrease and the distributed constants of the connecting leads play a continually greater part in the circuit performance. In the ultrahigh-frequency region and particularly at wave lengths less than one meter, it becomes convenient to do away with the lumped circuit constants altogether and to use instead the resonant properties of transmission lines of either the parallel wire or coaxial types.[77] Such circuits are readily adjustable, convenient to work with, and the mathematical theory of their properties is well understood. At still higher frequencies even transmission-line circuits become impractical but at this point the resonant properties of conducting cavities can be exploited to advantage. It was demonstrated about four years ago[79] that a cavity whose boundary is a good conductor is capable of sustained electrical oscillations at certain characteristic frequencies determined by its geometry and that such cavities may be used advantageously as circuit elements associated either with sources or sinks of electromagnetic wave power. In some recent electronic devices, for example the velocity-modulation tubes and klystrons mentioned above, this principle has been invoked. The tube elements themselves have in effect been set directly into the walls of such resonant cavities.[78]

Closely related to the phenomena of resonant cavities is the propagation of electromagnetic waves through hollow metal tubes or wave guides.[79–84] For simple geometrical shapes the theory of this form of electromagnetic wave propagation is well established.[80] Propagation can take place only when the wave length is less than some critical value which is of the same order of magnitude as the diameter of the conductor. The method is therefore limited to the ultrahigh frequencies. Attenuations even at these extremely high frequencies can be made comparable with those of ordinary coaxial cable at the lower frequencies so that at the moment wave guides appear to offer considerable promise in future wide-band ultrahigh-frequency communication systems. The end of a wave guide may be flared out into a highly directive electromagnetic horn which may be used either as a radiator or receiver of ultrahigh-frequency waves. The resulting power gains are comparable with or even greater than those of the more conventional directive antenna arrays now in general use.[85–8] The rapid development of the understanding of the transmission properties of ultrashort waves in wave-guide systems has provided a further impetus for the development of electronic devices capable of generating and amplifying these ultrahigh frequencies.

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No attempt has been made to make the bibliography comprehensive. The aim has been to include papers of most fundamental importance and, where they are available, those of a review nature which will assist the reader who wishes to go more fully into the developments of any particular field. Preference has been given to the literature printed in the English language since it has been felt that this will be of most use to the average reader. In so doing it has not been intended to slight the much excellent work on electronics and communications which has been carried on abroad.

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A Decade of Progress in the Use of Electronic Tubes

Part II—In Other Than the Field of Communication*

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Synopsis: The past ten years include nearly the whole period during which electronic tubes have been used outside the communication field. The types of tubes used in this field may be classified into groups, each having properties that make it valuable in certain phases of industry or in specific applications. The references are grouped according to nature of application and represent a selected group chosen by careful elimination from several thousand.

IN comparison with the communication field, the use of electronic devices in other industry has played an entirely different role. In communication in general and in radio in particular, tubes and tube developments have been basic to most improvements. They have been truly called the "heart" of nearly all radio apparatus. In other industry, however, they have in general had to supplant other methods and to compete in highly developed fields of electrical engineering.

The use of tubes in the noncommunication field has passed through several broad phases. At first they were looked upon with a certain amount of mistrust as being rather fragile playthings entirely unsuited for the severe conditions encountered in the industrial field. Next, as a result of the increased popular interest in science and the optimism of the late 20s, they became "wonder" devices and their wide use in nearly every electrical field was freely predicted.

Within the past few years, a more realistic viewpoint has prevailed and much solid progress has been made. It is realized that there is no magic in an electron tube, and the tube must either accomplish something that cannot be done by any other means or make its own way against competition solely on the basis of what it can do for less cost than existing methods.

Scope of This Review

The last decade includes the greater part of tube activity in this field, but reference is necessarily made occasionally to earlier work to clarify or to complete the picture.

Electrons are now known to play such an active part in so many devices that, in the interest of brevity, certain devices are not included in this review. These omissions are neon lights as well as other gaseous light sources, ultraviolet tubes, X-ray tubes, pumped mercury-arc tanks, iron-wire ballast tubes, mercury and vacuum switches, and uses in phonographs and talking moving pictures. This review is also limited to American references in the interest of brevity.

Due to the activity in this field and the relatively long period covered, only a small fraction of the available references are included. Those included were chosen on the basis of availability, general nature of treatment of subject, and their use of further references.

The emphasis in this review has been placed mostly on tube applications rather than the tubes themselves. This has been done because of the wider interest in applications and because the review must be kept to a reasonable length. The references to tube design have been included only when they were important from the viewpoint of new applications or unless similar tubes were not used in communication.

Arrangement of References

In general the references are classified under headings similar to those employed by the AIEE in indexing its TRANSACTIONS in past years.

Factors Favoring the Use of Tubes in Industry

In competing with rotating equipment, the use of tubes eliminates noise, vibration, and the need of special foundations.

The ability to amplify from very low input levels both in high-vacuum and gas-content tubes makes them unique electrical devices. Their amplification can also be made continuously variable rather than step-by-step.

Tubes provide cycle-by-cycle and fractional-cycle control.

Tubes in combination with such devices as thermocouples, microphones, photoelectric cells, and movable capacitance plates permit electrical response to temperature, sound, light, and motion. Therefore, they extend control operations to variations in sensory response.

Tubes also find ready application where they extend certain factors to extreme limits. Timing to very short intervals, response to extremely small electrical quantities, and control from very small movements are examples of this.

They operate relatively independent of frequency in comparison with most other electrical devices.

Factors Retarding the Use of Tubes in Industry

The relatively high cost of tubes in combination with the fact that they are renewable items has retarded their application.

Their mode of operation and application has not been so commonly understood as other electrical devices.

Considerable engineering knowledge and effort are often required to work out a new application successfully and in some cases the expense of this apparently cannot be justified from the viewpoint of available business.

A General Summary of Types of Tubes

The following comments are based on tube types and applications outside the communication field.

HIGH-VACUUM DIODES

These tubes are inherently rectifiers only and are suitable for use where high frequencies are involved. Their use is also limited in general to currents of about an ampere. They are suitable, however, for voltages up to the hundreds of thousands.

The early applications of this type of tube were for the purpose of obtaining high voltage (25 to 150 kv) for smoke and dust precipitation as well as high-voltage cable testing by power companies. This

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use has continued and grown to some extent. They also find a wide variety of application, but in limited quantities, in laboratories for high-voltage, low-current, d-c power supplies.

High-Vacuum Tubes With Control Grid or Grids

This class of tubes involves one or more control electrodes; their chief functions are as amplifiers and oscillators. They range in ratings from less than a watt to over 100 kw.

There are probably hundreds of thousands of these tubes in daily operation in a bewildering variety of circuits. By far the big majority of them are radio-receiving-tube types used in oscillating and amplifying circuits. In some cases, requirements of power output or a special operating condition has dictated special types. Automatic train control, high-frequency therapeutic oscillators, and low-grid-current amplifier tubes are examples of such special designs. There are many others.

The literature contains hundreds of articles on special applications of this class of tube and thousands of references are made to their use in the literature.

Hot-Cathode Gas-Filled Diodes

This class of tube is utilized for rectification of heavier currents at lower frequencies and voltages than the high-vacuum type. Gas-filled tubes have a relatively low and constant voltage drop in comparison with high-vacuum tubes.

There is one field where the great majority of tubes of this type are used and that is for low-voltage battery charging. Most of these are tungsten filament, argon-filled tubes for currents under ten amperes, and for direct voltages under 125.

Another group of rectifier tubes of this class utilizes mercury vapor and is suitable for voltages up to about 20,000. Although the great majority of such tubes are used for d-c power supply of radio transmitters, some are used for high-voltage testing and to supply direct current for high-frequency tube oscillators.

Similar tubes are also employed in rectifiers to supply power at the lower standard voltages—125, 250, 500, and 650—to replace power formerly obtained from a d-c Edison system or private generating plant.

Hot-Cathode Gas-Filled Grid-Controlled Tubes—Thyratrons

The control action of this type differs from the high-vacuum type in that only the start of the discharge is controllable. They are particularly suitable for controlling currents of a few amperes from a-c circuits. Their ability to control by cycles of the a-c supply leads to a number of valuable applications.

One of the earliest commercial applications for this type of tube was for the control of the illumination from incandescent lamps used in theaters and decorative lighting. In this application they functioned as controlled rectifiers to supply a variable direct current to saturation reactors. These latter functioned as variable reactors in series with the groups of lamps.

Within the past few years, applications have fallen largely into certain classes:

(*a*). Rectifiers to supply variable voltage or current from an a-c source of supply. This combination is employed to control d-c motors, field excitation of generators, and various electromagnetic devices.

(*b*). Inverters to supply either constant or variable-frequency a-c power (up to a limit of a few hundred cycles) from a d-c supply. As a variation of this the same general principle may be used for frequency changing.

(*c*). The use of a pair of tubes connected "back-to-back" so that in combination they pass alternating current. This gives a circuit element that not only acts as a contactor but by phase control of the grid voltage permits variation of the current passed. These tubes are so used in some welding control circuits where too large currents are not involved.

During recent years there has been a trend toward the use of inert gases, such as argon, neon, or xenon, to replace mercury vapor. This gives this class of tubes a freedom from ambient temperature effects that are sometimes troublesome with the use of mercury-vapor tubes. They are, however, not usable for peak inverse voltages up in the thousands as in the case of mercury vapor tubes. For small tubes to handle fractions of an ampere, the inert gas content also allows operation as an inverter up to thousands of cycles.

Cold-Cathode Glow-Discharge Tubes

These are particularly applicable where filament operating power is not available and where ample control voltage can be employed. These tubes are often equipped with control electrodes. They are characterized by a higher voltage drop than the hot-cathode or pool type of gas-content tube. Also the current-carrying capacities are limited to a fraction of an ampere average current except that currents up to a hundred amperes or more can be carried for very short periods of time.

The two-electrode form has a number of applications that may be classified as follows:

(*a*). As a discharge tube to break down at some abnormally high voltage and thus act as a circuit protective device.

(*b*). As a voltage regulating device to place across a circuit. This use results from the characteristic of such a tube, with proper design, to pass a wide range of currents with a nearly constant voltage.

(*c*). As a negative-resistance element to generate oscillations by the relaxation circuit principle.

(*d*). As a rectifier based on the dissimilarity of the two electrodes.

(*e*). To produce light in accordance with the pulses of current through the tube. The light produced may be extremely intense for a very short time as for stroboscopic work or modulated in accordance with a variable current intensity or frequency.

When one or more control electrodes are added, the characteristics of a relay are gained. The applications listed above are retained and in some cases their scope extended. To date the three-electrode form has largely found its usefulness in the communication field but has wide relay possibilities in industry as it becomes better known and further developed.

Photoelectric Tube

In industry the photoelectric tube is performing many functions not possible by other means. In addition it is becoming an important agent in eliminating routine human effort. In combination with an amplifying tube, it is finding its place in applications where the eye and the hand are needed but not the brain.

During the past ten years, photoelectric-tube applications in great numbers have been made and, due to their apparent news value, widely publicized. Development of the photoelectric tubes themselves has been along the lines of smaller size, greater sensitivity, selective response in the spectrum, and novel mechanical designs for special applications. Lowered cost has also been helpful in extending their use.

Their applications may be grouped into three general classes:

(*a*). Applications in which a light beam, when interrupted or established, actuates a photoelectric relay. Examples of this are sorting, counting, door opening, hole detection, alarm systems, safety devices, and miscellaneous control jobs in industry.

(*b*). Applications where the tube and its accessories are actuated by variation in the amount of light falling upon it. Examples of this are smoke detection, check on turbidity of solutions, photometry and radiation measurement.

(c). Applications utilizing the difference in response of photoelectric tubes to light from different parts of the spectrum either directly or by the addition of filters.

Photoelectric tubes may be grouped according to the combination of features they employ. These classifications are:

(a). High-vacuum or gas-filled to increase their sensitivity.

(b). Nature of photoemissive surface which controls sensitivity and response to different parts of spectrum including the ultraviolet.

(c). Design and composition of bulb to transmit or restrict light flux from different parts of the spectrum to the photoemissive surface.

(d). Variations in mechanical design to adapt the photoelectric tube to special uses involving size, nature of base and direction, and degree of solid angle from which radiation reaches the photoemissive surface.

Existing photoelectric tubes have various combinations of these features.

Photovoltaic cells and selenium cells have not been considered within the scope of this review.

Pool Tubes—Ignitrons

The outstanding characteristic of the pool cathode is its ability to pass very heavy currents—thousands of amperes. The addition of the ignitor gives the pool tube control characteristics. By phase control, voltage and current regulation are obtained and, by cycle control, short-time switching functions.

For a considerable number of years, preceding about 1933, the sealed-off pool type of tube had been slowly experiencing a decline in usefulness. Its chief applications were battery charging and high-voltage rectification for series arc lamps for street lighting. These were not growing applications. Then two new developments appeared which changed this picture completely. One was the ignitron and the other was the sealed steel envelope. The first solved the starting problem and gave the pool type the equivalent of grid control. The latter made large tubes and water-cooling practical and the tubes more acceptable to industry.

Since 1933 the use of pool tubes has grown steadily. Most of this growth has been in the welding control field where the tube's ability to carry very heavy peak currents has been an all important factor. The use of the sealed-off steel envelope ignitron for power conversion rectifiers for outputs between 75 and 350 kw has begun and appears to be a promising field.

Cathode-Ray Tubes

In industry the use of a fine beam of electrons to produce and control a light spot on a fluorescent screen for oscillographic purposes is most common. These tubes can also be used for various forms of indicators.

For many years cathode-ray-tube oscillographs were considered as laboratory devices only but now they are commonly employed by electrical engineers and are necessities for many measurement problems. A better understanding of them, together with better-designed equipment and lowered cost, have been the chief contributions.

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Measurements at Radio Frequencies

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IT IS interesting to recall that this art is less than a century old[1] and that the early experimenters[2] actually worked in the frequency range now called "hyper frequencies."

The same basic principles are used at power frequencies and radio frequencies in the measurement art but the different techniques and nomenclatures often obscure this fact. These differences have arisen because the magnitudes of the fundamental quantities usually are widely separated. As the frequency is increased, the circuit usually changes markedly[3] since elements which are negligible at one frequency often become important in the new range. Size, design, and required accuracy also affect measurement problems.

It is the purpose of this paper to discuss the more common measurement problems at radio frequencies and to give a résumé of the status of this rapidly growing art.

Measurements of Voltage

The primary standards of voltage at radio frequencies are actually the usual d-c standards, and measurements are made by means of transfer instruments. The most popular instrument is the vacuum-tube voltmeter[4] which is available in forms ranging from the simple diode rectifier to a multitube inverse-feedback amplifier. All forms have the following characteristics in common: high input resistance, 0.25 to 10 megohms; low input capacitance, 1.5 to 30 micromicrofarads; response proportional to peak or average value, depending upon design; flat frequency response over the range for which they are designed, and they require a power supply. Because some forms of this instrument are so reliable and versatile, it is really no problem to measure radio-frequency voltages for a wide variety of conditions. The problem of obtaining a voltage measurement without affecting the voltage being measured is more common at radio frequencies than it is at power frequencies. The acorn-type vacuum tube is generally useful when this problem is encountered because of its small size and good electrical characteristics. Even under conditions which require that the small capacitance of this tube be compensated for, good measurements have been obtained. In fact, with proper technique, the acorn diode has given satisfactory operation at 300 megacycles per second. Conditions sometimes require that the diode voltmeter be built into the circuit[5] to avoid the errors which would result from moving even such a small device from one part of the circuit to another.

The vacuum thermocouple[6] is also a useful transfer device at radio frequencies because of the following characteristics: small frequency corrections, one calibrated on direct current has a correction less than one per cent at 100 megacycles per second; response to effective value regardless of wave shape; small size; and it is a passive network, primarily resistive. In addition, there is the cathode-ray tube which is rapidly gaining favor because it gives information as to wave form and frequency as well as magnitude. At present, it is much more expensive and more difficult to use than the other devices.

The radio engineer is often concerned with the microvolt, but none of these instruments is sufficiently sensitive to measure such small voltages so indirect means are employed to effect these measurements. A common way is by comparison with a voltage obtained by attenuating a voltage of the order of one volt by known amounts.[7] Another way to obtain microvolts is to generate them with a microvolt generator or second harmonic generator.[8] Figure 1 shows one form of the microvolt generator, and figure 2 is a schematic diagram of it. It is a full-wave rectifier so connected that the usually unwanted ripple current is used to generate a known voltage across the known impedance, Z. It depends upon the fact that if the tube characteristics are square law, the only output will be at twice the frequency of the input voltage and the peak value of this output

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1. For all numbered references, see list at end of paper.

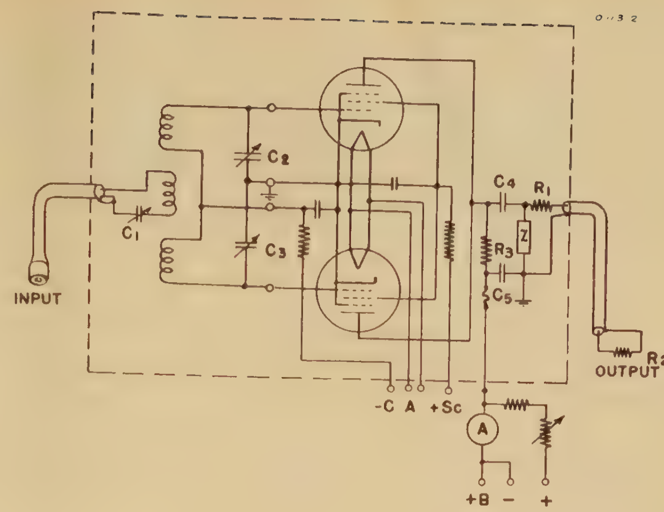
current will be equal to the change in direct current in the plate circuit. When the tube characteristics depart from the square law, higher-order even harmonic currents are generated. It has been found practical to use the sixth harmonic. The essential fact is that no fundamental or odd harmonics are present and the radio-frequency current is indicated by a d-c microammeter.

When special problems arise, such as measuring 0.1 microvolt, which cannot be readily solved by either of the methods described, it is usually wise to refer to the work of Faraday, Maxwell, Hertz, and other pioneers. A mutual-inductance attenuator based on Maxwell's formula[9] and tested at high level was found easy to construct, test, and use to obtain voltages of the order of 0.1 microvolt at 40 megacycles per second.

The problem of measuring high voltages at radio frequencies is usually solved by using some form of multiplier with a moderate-voltage instrument as it is at power frequencies. The problem of designing the multiplier has no satisfactory general solution, but when capacitance dividers cannot be used, a tuned circuit or a quarter-wave section of transmission line may provide the solution.

The problem of inventing a practical standard of voltage at radio frequencies is fascinating and tantalizing. The phenomenon of resonance potential[10] in gases appears to have promise. A tube in which this phenomenon was observed is shown in figure 3. It consists of an anode and cathode sealed into a tube along with a drop of mercury and a coating of zinc sulphide. The anode is like the grid of an ordinary vacuum tube so that many of the electrons will go beyond it to strike mercury atoms. Those electrons having an acceleration of 4.87 volts cause radiation at a wave length of 2,537 angstrom units and this radiation is made visible by the fluorescence of the zinc sulphide. The problem remaining is to get precise correlation between the impressed voltage and the resonance potential. There must be a way to harness the electron.

Figure 2. Schematic diagram of microvolt generator



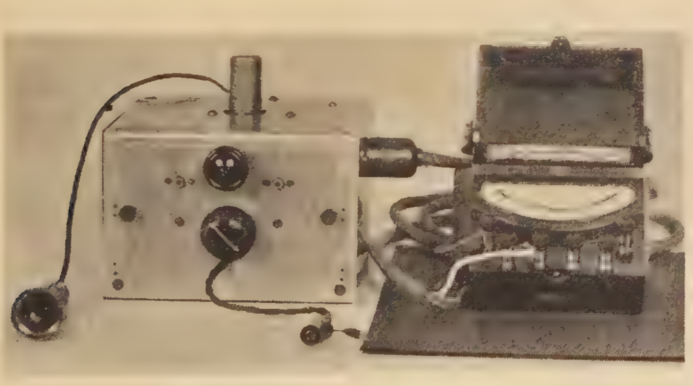


Figure 1. Microvolt generator with indicator

Measurement of Current

The primary standard of current at radio frequencies is the oscillating-ring type of electrodynamic ammeter,[11] figure 4. Although unconventional in its method of indication, the oscillating-ring type of electrodynamic ammeter is simple. It is essentially a metal ring, free to rotate about a diameter, and immersed in an electromagnetic field produced by the current being measured. The field tends to orient the plane of the ring parallel to the flux lines with a torque proportional to the mean square current and to the small angular displacements of the ring's plane from this torque node. Therefore, if the ring is mechanically displaced and then released, it oscillates about the torque node, until damping brings it to rest, with a frequency of torsional oscillation proportional to the rms current. To obtain the value of a current, then, instead of noting the deflection of a pointer on a scale, the observer determines the mechanical frequency, F_m, of oscillation of the ring.

The actual measurement required for each determination is that of time, a fundamental measurement which can be made with great accuracy. Mathematically, the high-frequency current is given by the equation,

$$I=\left(\frac{2\pi\sqrt{JL}}{m}\right)F_m$$

where J, L, and m, are the ring's moment of inertia, inductance, and coefficient of mutual inductance with the exciter and are calculable from measurements of lengths and mass which need be made but once for the instrument. Since the fundamental measurements of length, mass, and time suffice for the determination of current in this instrument, it is a primary standard. That the required measurements of length, mass, and time can be made, and the necessary computation carried out, with accuracy, has been demonstrated by checking several different designs of vibrating-ring electrodynamic instruments against thermocouple ammeters at frequencies below the thermal error range of the latter.

As to structural details of this type of instrument, the exciter or current-carrying circuit, in whose field the ring is placed, is not restricted to any one form. For example, a single circular loop has been found useful for low currents and a single toroidal turn (figure 4) for large currents. In any case, its form does not require high inductance, nor does its function require an energy-consuming heating effect. Neither is large shunt capacitance, inherent in the temperature equalizing terminals of thermocouples, at all necessary.

The support for the ring may be a simple fiber suspension, or jeweled bearing for greater sturdiness.

The determination of the mechanical frequency of the ring's oscillation may be done quite closely by an observer with a

Figure 3. Critical-voltage tube

stop watch, or with greater precision by a light beam and photoelectric relay in conjunction with a two-pen tape chronograph and a time standard.

The oscillating-ring type of electrodynamic ammeter possesses a unique combination of characteristics. In contrast to the deflection types[12] of electrodynamic instruments, its impedance is independent of current, and it is not subject to loss of precision nor to limitation on maximum current by a cramped scale. As in other electrodynamic ammeters for high frequency, the effect upon its indication, produced by raising the frequency of the current, is calculable and small. In contrast to the effect in thermal ammeters, it decreases with increasing frequency. This follows from the fact that whereas thermal ammeters depend upon effective resistance which continues to increase with frequency, electrodynamic instruments depend upon flux linkages or inductance which approaches a fixed limit as frequency is raised. For example, in a conventional five-ampere thermocouple, the change in indication was calculated to be 1.6 per cent between 0.5 and 5.0 megacycles, and over 40 per cent between 5 and 50 megacycles; whereas in one electrodynamic instrument used, the corresponding figures were 0.77 per cent between 0.5 and 5 megacycles, and only 0.25 per cent between 5 and 50 megacycles.

A secondary standard of current at high frequencies, like one at power frequencies, should be capable of insertion in a circuit without seriously affecting the operation of either the circuit or the instrument. Furthermore, essentially all the radio-frequency current led to the "high" terminal should traverse the actuating element, and no indication should be had from strong surrounding fields. It is also desirable that high-frequency error in the actuating element be minimized.

The design of a low-impedance thermocouple-type ammeter indicates the methods applied to meet these requirements. In this low-impedance design, the actuating element or heater is a thin flat ribbon doubled back on itself with a thin mica separator between its inner surfaces. In order to preserve the advantages of minimum inductance and negligible stray fields inherent in this type of heater, its supporting studs are made short and concentric. The center stud, having its external end flattened and drilled to serve as the ammeter's "high" terminal, visible in figure 5, intrudes through an insulating bushing in a small shallow cup so that it makes contact with one flat end of the heater whose other end, opposite the mica separator, is mounted on the center of the cup's bottom. The cup, shown removed from the ammeter in figure 6, is recessed in the ammeter's back plate which itself serves as the external "low" terminal, seen in figure 5. The shielding effect of this concentric "low" terminal is continued about the miniature d-c instrument by the small contiguous metallic case and scale plate.

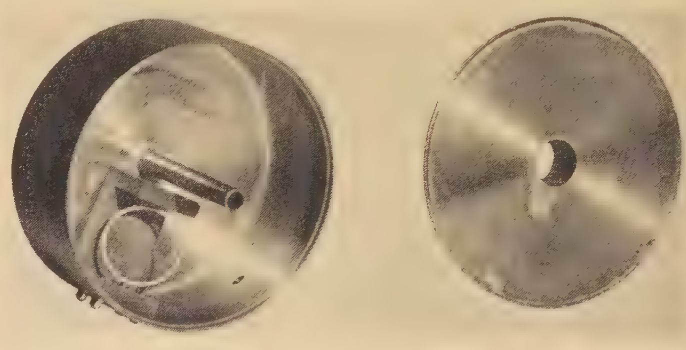


Figure 4. High-frequency electrodynamic ammeter

The effect on performance at high frequencies, which the above features of design have produced in the low-impedance thermocouple-type ammeters, is indicated by the results of comparative tests such as those described below.

For example, two conventional "high-frequency design" thermocouple ammeters when placed in series, read alike at 32 megacycles, one per cent different at 42 megacycles, and three per cent different at 52 megacycles; but these same instruments when individually placed in series with the low-impedance type instrument, with the latter in the "low" side of the circuit, each read the same as the low-impedance ammeter.

A further indication of the low impedance of this type of instrument is given by the fact that when applied as a series resonance indicator in a conventional wavemeter circuit, it allowed extension of the top frequency from about 150 to 360 megacycles at the same time permitting the use of a larger inductance loop. The wavemeter[13] smoothly covered a band from 160 to 360 megacycles, with a capacitor of 25 micromicrofarads maximum capacitance and an inductance comprising slightly more than one turn one inch in diameter in addition to the capacitor leads. The inductance of the instrument is 0.005 microhenry.

The effectiveness of its shielding has been demonstrated in a test in which a number of thermocouple-type ammeters, including both the low-impedance and conventional types, were placed directly in radio-frequency fields. Between 15 and 90 megacycles, the ammeters were placed within one-quarter inch of the tank coil of a 50-watt oscillator, and between 260 and 380 megacycles they were placed in the maximum field of the tank lines of a line-controlled 15-watt oscillator. Although conventional-design ammeters during these exposures, with no current actually applied, gave readings ranging from zero at lower frequencies to more than full scale at higher frequencies, the low-impedance type instruments under the same conditions uniformly maintained a reading of zero.

Thus, when the low-impedance thermocouple-type ammeter is inserted in a circuit, it introduces a minimum of reaction on the circuit, remains unaffected by surrounding fields, and indicates no more nor less than the current entering its "high" terminal. In addition to the demonstration of these characteristics prerequisite in a secondary standard of high-frequency current, further tests have shown that skin-effect error at high frequencies in the doubled-ribbon heater has been greatly reduced below that found in the solid-wire type of heater.

The concepts of Faraday are particularly helpful in problems of measuring current at high frequencies, because when high-frequency currents of any size flow, the fact that the energy is in the fields becomes apparent. For example, men standing six to eight feet away from a ten-kilowatt oscillator operating at 75 mega-

cycles have felt their ankles get warm. This approach to a current-measuring problem leads to correct application of available instruments because the way high-frequency currents divide in a particular circuit becomes reasonable when the fields are considered. When a spacer is thought of as a dielectric medium rather than as an insulator, the "mysterious" loss of current in a circuit becomes an expected occurrence.

Measurements of Frequency

A primary standard of frequency is an oscillator whose rate is substantially constant when determined by counting the number of oscillations and dividing it by the time taken to produce them. The unit of frequency is, therefore, based on the standard second which is 1/86,400 of the mean solar day or 1/86,164.100 of the sidereal day. The National Bureau of Standards maintains several primary standards of frequency and makes some of them available for general use by means of standard frequency transmissions over station WWV, Beltsville, Md. Many laboratories maintain primary standards of frequency by using the WWV standard frequency transmissions and the United States Naval Observatory time signal[14] transmissions to check them. The counting of radio-frequency oscillations may be accomplished by means of a combination of electronic counter circuits and a mechanical counter. The multivibrator[15] or relaxation oscillator is commonly used for the electronic counter and a synchronous-motor clock for the mechanical counter. Rates constant to one part in ten million are commonly obtained by means of quartz-crystal-controlled oscillators operating at 100,000 cycles per second.

In many cases, a signal from the oscillator or transmitter whose frequency is to be determined can be brought to the primary standard and the measurement made by direct comparison. When this is not practical and an accuracy of 0.1 per cent is acceptable, the common absorption-type wavemeter consisting of an inductor and a capacitor connected in series can be used. The operation of this device depends upon the following relation between frequency, inductance, and capacitance:

$$f=\frac{1}{2\pi\sqrt{LC}}$$

When greater accuracy is required, some form of the heterodyne wavemeter may be used. The heterodyne wavemeter is a calibrated oscillator which can be tuned to the frequency of the unknown signal with great accuracy by one of the beat note methods. When a quartz-crystal-controlled oscillator is used to check the calibration of the heterodyne oscillator, an accuracy of 0.001 per cent can be obtained.

The problem of measuring higher and higher frequencies stays with us as the art progresses. In most cases, the first need is a suitable receiver for the unknown signal and the problem remaining is to set a high-frequency oscillator accurately on a harmonic of the standard. For example, adjust a 1,000-kc crystal to the tenth harmonic of the 100,000-cycles-per-second standard, then set a 10,000-kc crystal oscillator on the tenth harmonic of the 1,000-kc oscillator. This process can be carried as far as necessary to provide guide posts in the upper frequency spectra.

Since frequency can be measured so accurately, it is highly desirable to be able to use it as the indicator when measuring other quantities. For example, an excellent way to measure small changes of capacitance[16] is to put the capacitor in an oscillating circuit so that these changes cause changes in frequency which can be monitored continuously and accurately.

Measurements of Power Factor and Dielectric Constant of Materials

It is as important to know the power factor and dielectric constant of an insulating material used in a radio transmitter as it is to know the power factor of a load on a power line. The power factor of a material is the cosine of the angle whose cotangent is the ratio of conductance to susceptance in the sample when it is used as the main dielectric in a two-electrode capacitor. This is based on representing the sample by a pure resistance in parallel with a pure capacitance. It may also be represented by a resistance in series with a capacitance and then the power factor is the cosine of the angle whose cotangent is the ratio of resistance to reactance.

Power-factor standards can be made of disks of pure, clear fused quartz because the power factor is 0.0002 from 1 to 3,000 megacycles per second. The bases of this statement are a determination at 3,000 megacycles by W. C. Hahn, engineering general department, the work of Von Lothar Rohde[17] at 200 and 500 megacycles, and the work of this laboratory.

There are many ways[18] of measuring the power factor of a material at frequencies less than one megacycle per second. Some of the circuits available are: parallel bridge, series bridge, resistance variation, substitution, and reactance variation.

At frequencies above one megacycle, the reactance-variation[19] type of circuit has been popular. This popularity probably resulted from the fact that power factor is determined by measuring capacitances, changes of capacitance, and ratios of voltages. Variable capacitance of known value is easier to obtain than variable resistance at frequencies above one megacycle. The procedure is to measure the width of the resonance curve for a certain ratio of voltage at resonance to voltage off resonance with the sample capacitor tuning the resonant circuit and repeat this with an air capacitor in place of the sample. These data are sufficient for two separate circuit-resistance determinations and, therefore, for the effect of the sample on the circuit. Since the measurement of power factor is a resistance measurement, the following factors in addition to those in the measuring equipment are important: the size and shape of the sample; the size, shape, and material of the electrodes; and the method of applying the electrodes to the sample. The size and shape of the sample are major determining factors of the capacitance. If this capacitance is made small compared to the inherent capacitance of the measuring circuit, it will obviously become difficult to determine the effect of inserting the sample. On the other hand, if it is made large, its reactance will approach that of the residual inductance in the measuring equipment and will cause resonance effects and consequent inconsistent operation. The size and shape of

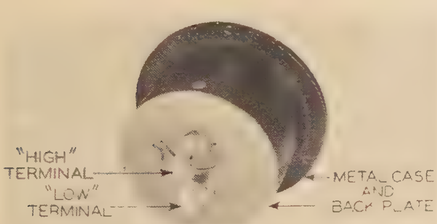


Figure 5. Low-impedance thermocouple ammeter (rear)

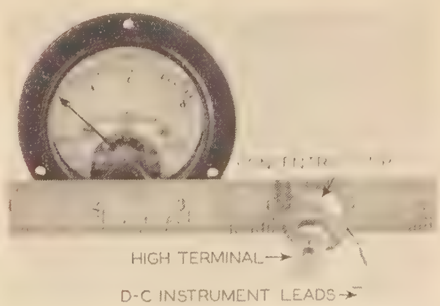


Figure 6. Low-impedance thermocouple ammeter (front)

the electrodes also affect the capacitance, but the effective resistance of the electrodes is often the more important factor.

Because there are so many possible sources of error, it is good to have a clear fused-quartz standard sample to test the over-all operation of any power-factor measuring equipment.

The dielectric constant of a material is the ratio of the capacitance of a pair of electrodes with the dielectric between them to their capacitance for the same spacing in a vacuum. It is necessary to choose the electrode geometry properly[20] to allow accurate determination of the dielectric constant when the sample size is fixed. The capacitance of the sample is usually a by-product of the power-factor measurement procedure.

Measurements of Impedance

One way to determine impedance is to measure the current through and the voltage across the unknown impedance and calculate the ratio of E to I. Even at power frequencies, it is not convenient to use this method and at radio frequencies it is seldom convenient to use. One reason for this is that one-inch leads are the same part of a wave length at 63.36 megacycles per second as one-mile leads are at 1,000 cycles per second. It is hard to overemphasize the need for short leads from the measuring equipment to the unknown impedance.

In addition to requiring short leads, the problems which have arisen frequently since the advent of television have required that the measuring equipment be portable where portable means that the user can carry it up an antenna tower and use it at the top. An instrument for this service in the 40 to 70 megacycles per second frequency range is shown in figure 7 and a schematic diagram is shown in figure 8. It will be noticed that provision has been made to obtain short leads. At the same time, the measuring circuit was shielded from the oscillator and from external fields by placing it in a separate metal compartment, by providing Faraday screens between the oscillator coil and one coupling coil and between the other coupling coil and the measuring circuit coil, and by using a common ground.

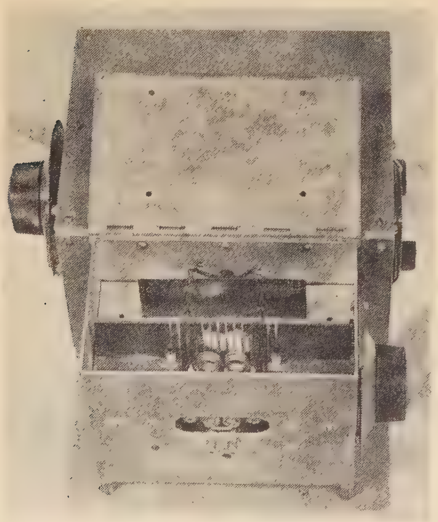


Figure 7. Portable impedance measuring instrument

The measuring circuit is a coil and a capacitor so arranged that either balanced or single-ended impedances can be measured by the reactance-variation method. The parallel tuned circuit has been so arranged that the unknown can be connected in series with the coil and consequently low values of impedance can be measured. The usual parallel connection of the unknown is also provided for high values of the unknown. The procedure is to determine the circuit constants with and without the unknown connected in terms of capacitance, change of capacitance, and voltage ratios. The differences between the two resulting sets of susceptance and conductance values are the constants of the unknown impedance.

This instrument was used in the installation of the transmission lines and antenna of General Electric television station W2XB in band 3 (66 to 72 megacycles).

It is often necessary to measure the inherent inductance in low-value resistors. One way to measure these small inductances is to use the microvolt generator.

The procedure is to insert a resistor, R_1, as Z and measure the current, i_1, which causes a certain output at frequency, f_1; replace R_1 by a different resistor, R_2, and find the current which causes the same output; repeat this procedure at another frequency, f_2, and solve the resulting simultaneous equations:

$$i_1\sqrt{R_1^2+(2\pi f_1 L_1)^2}=i_2\sqrt{R_2^2+(2\pi f_1 L_2)^2}$$

$$i_1^1\sqrt{R_1^2+(2\pi f_2 L_1)^2}=i_2^1\sqrt{R_2^2+(2\pi f_2 L_2)^2}$$

In a particular case, a two-ohm and a ten-ohm resistor were used at 25 and at 40 megacycles. The inductance of the two-ohm resistor was 0.016×10^{-6} henry. The impedance of the two-ohm resistor is, therefore, 3.20 ohms at 25 megacycles and the necessity for determining inherent inductance in low-value resistors is evident.

Measurements of Transmission Line Characteristics

In television transmitting systems as in other radio transmitting systems, it is usually impractical to locate the transmitter unit adjacent to the antenna. A transmission line is employed to connect these parts, and for the wide-frequency-band operation needed in television communication, the transmission line must have quite definite characteristics.

Physically such a transmission line usually consists of straight sections of concentric tubes with spaced low-loss beads for insulation. Sections are joined at corners by means of junction boxes and the inner conductor is supported in long vertical runs by means of an anchor joint. To secure proper performance of the transmission line, it is necessary to compensate for the electrical disturbances produced by these junction boxes and anchor joints. It is also necessary to match the antenna circuit to the transmission line

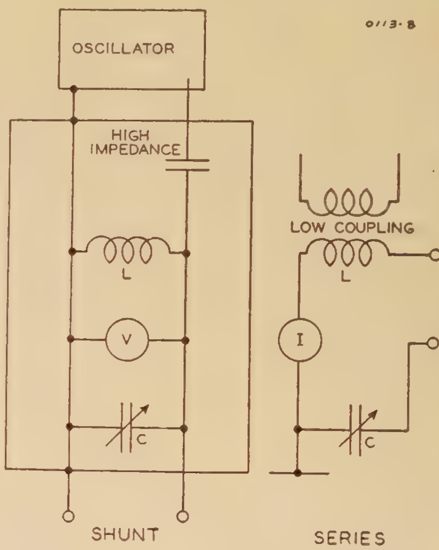


Figure 8. Schematic diagram of measuring instrument

much more closely than was commonly practiced in communication or broadcast transmitter systems. For these reasons, it is desirable to measure the characteristic impedance of the line and to determine its frequency characteristic with compensating elements added at the required positions.

The reactance-variation type impedance-measuring instrument already described can be used to measure the characteristic impedance of the line, but it is not convenient to use this instrument for determining the frequency characteristic of the line. This may be done more easily by measuring the ratio of output to input voltage over the operating range of frequency. In practice, it has been found desirable to hold the input voltage constant which makes the output voltmeter indication proportional to the ratio wanted.

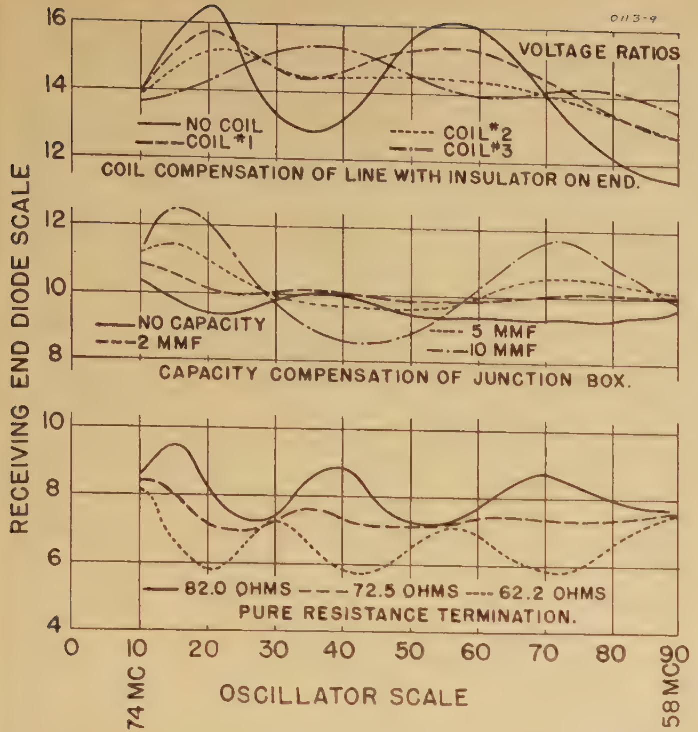


Figure 9. Experimental voltage-ratio curves

It is necessary that the ratio of output to input voltage remain practically constant over the operating-frequency range and desirable that it remain so over a wider range to give a safety factor. The information given in plots of voltage ratio versus frequency is shown in figure 9. The lowest set of curves shows that resistance terminations can be readily identified as lower or higher than characteristic impedance of the line. The middle set shows how changes of capacity at a junction box caused marked and easily recognized changes in the ratio curves also. The top set demonstrates the case of coil compensation.

When this method of measuring transmission-line characteristics is used, it is desirable to start with a short section and to add junction boxes, other sections, and anchor joints one at a time. If several things are added at once, the voltage-ratio curves become difficult to interpret; but if one thing is added at a time, the curves are as easy to interpret as those shown. A mathematical treatment of these relations is in the literature.[21]

That complete transmission characteristics over wide frequency ranges can be secured by properly using a pair of diode voltmeters is encouraging.

Conclusions

How basic principles are used in making measurements at radio frequencies has been shown in a number of cases.

Something of the range of the subject has been suggested by the diode voltmeter and the "critical voltage" tube.

A primary standard of current at high frequencies has been described.

A new low-impedance thermocouple ammeter has been presented.

Clear fused quartz has been proposed as a standard of power factor in the 1 to 3,000 megacycle-per-second frequency range.

A typical technique of making measurements at radio frequencies has been disclosed by the description of the "reactance-variation" method of measuring impedance.

It is hoped that the material presented will prove informative to engineers not directly connected with radio-frequency measurement work as well as to those in it.

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The Dielectric Strength and Life of Impregnated-Paper Insulation—II

The Influence of the Thickness of the Paper

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FELLOW AIEE

THE peculiarly severe conditions imposed by manufacture, transportation, installation, and operation of high-voltage cables have emphasized the importance that full attention be paid to all physical properties of the insulation, especially those relating to permanence of mechanical structure and of high insulating properties. The requirement of wide flexibility is at the root of the present method of applying the paper insulation in spiral tape form in successive layers.

Mechanical flexibility and high dielectric strength do not always go hand in hand. They do so to an astonishing degree in the case of impregnated paper. However, with the available materials it is not always possible to retain at the same time the maximum of flexibility and the maximum of dielectric strength and stability. Consequently in cable design, in order to meet the special requirements of particular cable installations, it is necessary to make such selection of the paper to be used as will ensure the optimum combination of flexibility and dielectric strength. Carefully prepared wood-pulp paper with low content of electrolytic impurity is now used almost exclusively for the type of insulation in question. It is available over fairly wide ranges of density and thickness, as determined largely by experience in manufacture and usage over the past 20 years or more. It is within these ranges of paper structure that the cable engineer finds the possibility of selecting papers for a very wide range of type of cable and conditions of service. The fact that impregnated-paper cables are giving highly satisfactory service for large blocks of power in the highest range of values of voltage is an indication not only of the remarkable insulating properties of this type of insulation, but also of the resourcefulness and persistence of cable engineers in experimental study and manufacturing skill.

In a related paper,[1] the present author has reported the results of a study of the influence of a variation of the density of the paper on dielectric strength as determined in a fixed program of accelerated voltage-time tests. The results of the study were at some variance with commonly accepted ideas[2] as to the influence of paper density on dielectric strength. They confirm the suggestion that has been made from time to time[3] that proper consideration must be given to the laminated form of construction, to the open spaces between successive tapes, and to the different values of dielectric constant of impregnated paper and of oil. In view of the positive character of the results and of their possible bearing on cable design, the work on the influence of density is continuing in order to explore the possible influence of other variables.

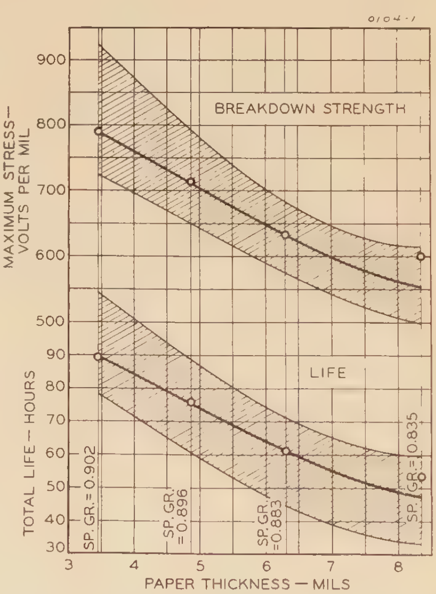

Figure 1. Breakdown strength and life as function of paper thickness

The present paper describes a similar series of studies on the influence of the thickness of the paper on dielectric strength and stability, as indicated by accelerated voltage-time tests. Here too it will be found that the results are of definite character and again indicate the importance that careful attention be given to the variations in the internal structure of the insulation wall.

The Papers

High-grade cellulose paper for cable manufacture is available in the range of thickness 0.0035 to 0.008 inch (3.5 to 8 mils, 0.0089 to 0.02025 centimeter). For the present studies four thicknesses of approximately 0.0035, 0.0048, 0.0063, and 0.00835 inch were used. The papers were supplied by a well-known manufacturer in the form of tapes one inch wide. It was intended that the density of the paper structure be the same for each thickness. As measured, however, the density of the 8-mil paper fell slightly below the others (see table I). We refer to the papers briefly as having nominal thicknesses 3, 5, 6, and 8 mils respectively.

The Test Specimens

The test specimens were made by wrapping the paper tapes on smooth brass tubes with $33^1/_3$ per cent and $66^2/_3$ per cent overlay with a butt spacing of the tapes of approximately $^1/_{64}$ inch (0.00397 centimeter). The number of layers of each thickness of paper was so chosen as to give approximately the same over-all thickness of all test specimens. (See table I.)

Nine identical specimens were constructed from each thickness of paper. They were dried and impregnated in groups of three. All specimens were impregnated with a light oil as used for oil-filled cables by American manufacturers.

Further details as to the measuring and guard electrodes, reinforced ends, etc., of the test specimens, of the physical characteristics of the oil, and of the methods of drying and impregnation will be found in earlier papers.[4]

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1. For all numbered references, see list at end of paper.

Experimental Method

All tests were made on single specimens immersed in the impregnating oil in a bath enclosed in a thermally insulated box with automatic temperature control.[5] The air pressure in the test box was that of the atmosphere. The temperature for all tests was 40 degrees centigrade.

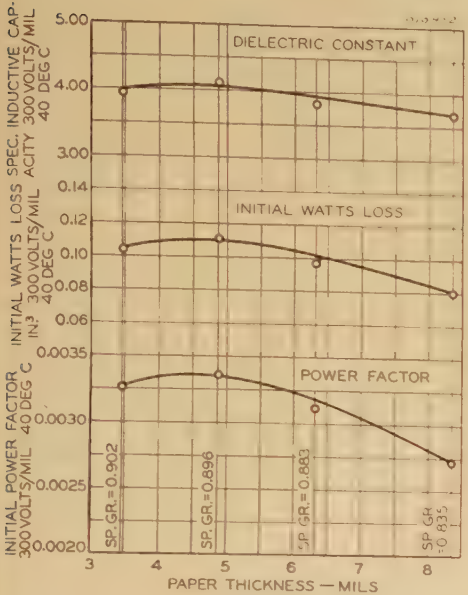

Figure 2. Dielectric constant, dielectric loss, and power factor as function of paper thickness

Life and Breakdown Tests. The accelerated voltage-time tests started at a voltage to give an average stress of 400 volts per mil on the specimen and the test voltage was increased by 3.12 per cent every four hours, thus giving a geometric increase such as to bring the stress to 700 volts per mil within three days. Under this program the range of life of all specimens tested was from two to four days.

Power Factor and Capacitance. Power factor and capacitance were measured over the range 100 to 400 volts per mil on a high-voltage Schering bridge[5] at the beginning of the voltage-time test and at 12-hour intervals.

Conductance. The long-time d-c conductance of the dry paper specimen was measured at 1,500 volts and 105 degrees centigrade before impregnation, and of the impregnated specimen at 60 degrees centigrade immediately following impregnation.

Experimental Results

The results of the accelerated voltage-time and breakdown tests on the three-mil paper are given in table I. They are typical of the results on the other thicknesses of paper, for which the average values only are given in the table. Using the average values of breakdown stress, as given in table I, the results on breakdown strength and accelerated voltage-time and other electrical properties are plotted in figures 1 and 2. The shaded areas represent the extreme limits of the spread of the test values. The average spread is substantially lower as seen in table I.

The results indicate that with increasing thickness of the paper, there are marked variations in all the electrical quantities, as well as the values of breakdown stress and life.

Breakdown Strength and Life. Both these quantities decrease with increasing thickness of paper, over the range studied. (See figure 1.) This similarity of behavior is a necessary consequence of the type of accelerated voltage-time test. Since the life run begins with a stress of 400 volts per mil, it happens that the percentage change in over-all duration of time (life to breakdown) is greater than that of voltage. The decrease in the average values of breakdown stress is from 788 to 602 volts per mil. This indicates a decrease in breakdown strength of something more than 25 per cent as between the three-mil and the eight-mil papers. This decrease would have been about 28 per cent if the specific gravity of the eight-mil paper had had the same value as that of the other papers. Discussion of these results and a probable explanation will be found in a later paragraph.

Dielectric Constant. Over the range of thickness studied there is a small decrease in the value of dielectric constant (see figure 2). This is apparently due to the slight decrease in density with increasing paper thickness. Corrected[1] for this variation, the value of the dielectric constant is very closely the same for all thicknesses.

Dielectric Loss and Power Factor. Both these quantities show a noticeable decrease in value with increasing paper thickness. Of the total change in power factor approximately 40 per cent may be attributed to the change in paper density.[1] The fraction of the total change

Table I. Accelerated Voltage-Time Tests—Influence of Paper Thickness

Specimen	Number Layers	Paper Thickness	Density J.H.U.	Oil:Paper Ratio by Weight	Breakdown (Volts Per Mil)	Hours at Maximum	Total Hours	Power Factor at 300 Volts Per Mil	Dielectric Loss (W/in.³ at 300 Volts Per Mil)	Capacitance (μμf, at 300 Volts Per Mil)
34-*A*	23	0.00353			770	3.8	87.8	0.00318	0.1010	608
34-*B*	23	0.00351			770	2.6	86.6	0.00312	0.979	602
34-*C*	23	0.00344			820	3.0	95.0	0.00318	0.1015	624
35-*A*	23	0.00342			722	2.2	78.2	0.00332	0.1030	611
35-*B*	23	0.00345			745	3.1	83.1	0.00338	0.1069	616
35-*C*	23	0.00344			745	2.7	82.7	0.00334	0.1072	627
36-*A*	23	0.00350			795	1.5	89.5	0.00331	0.1068	620
36-*B*	23	0.00337			928	1.2	109.2	0.00327	0.1057	644
36-*C*	23	0.00338			795	2.6	90.6	0.00322	0.1031	636
Average		0.00345	0.902	38.8	788	2.5	89.2	0.00326	0.1038	621
Maximum deviation					17.8%					$K = 3.94$
Average deviation					5.28%					
Specimen 22-24										
Average	(16)	0.00487	0.896	40.2	727	1.48	78.0	0.00336	0.1102	651
Maximum deviation	(16)				17.6%					$K = 4.11$
Average deviation	(16)				5.64%					
Specimen 37–39										
Average	(12)	0.00631	0.883	42.1	633	2.3	61.3	0.00312	0.0969	634
Maximum deviation	(12)				7.26%					$K = 3.82$
Average deviation	(12)				3.95%					
Specimen 40–42										
Average	(10)	0.00835	0.835	49.1	602	1.6	53.6	0.00272	0.0802	550
Maximum deviation	(10)				20.0%					$K = 3.69$
Average deviation	(10)				7.35%					

due to this cause in the case of the loss is approximately 30 per cent. Apparently, therefore, some factor other than density is playing a part in these decreases.

Oil Content. The oil content of the impregnated paper tape alone expressed as the ratio by weight of oil to paper is given in table I. It will be seen that the volume of oil absorbed increased approximately uniformly with increasing thickness of paper from the value 38.8 per cent for the three-mil, to 49.1 per cent for the eight-mil paper. This variation also is accounted for by the variation in paper density.

Type of Breakdown. All specimens were carefully examined after failure as to evidence of its beginning and cause. In the latter half of the work these studies were greatly facilitated by the use of a thyratron tube, relay, and rapid circuit breaker[6] for interruption of the primary circuit of the transformer. The operation of this device is so sensitive and rapid that not only is the usual burning attendant upon breakdown very greatly reduced, but in many cases the circuit is opened before the failure has extended further than two or three layers of paper. Further details of the operation of this equipment are given in the paper already referred to on the influence of the density of the paper on breakdown and life.[1]

Failures took place almost invariably under the central electrode of the test specimen and all failures have been of definitely radial type.

A clear indication of the foregoing studies on density, and of the present studies, is that most of the failures begin in the oil channels between successive turns of paper, most often at the central high-voltage electrode, sometimes in the center of the insulation wall, and in a few cases at the outer electrode. In a number of cases in which the specimen was dissected after the first two or three shots, the incipient failure was found to be confined to two or three layers. At one point the oil in a channel would be found to have become black, the blackening extending a short distance either way along the channel and along the edge of the paper. The next stage would be the puncture of one or perhaps two paper layers, but generally reaching the next oil channel on the same radius. Occasionally longitudinal tracking and tree patterns to adjacent channels were noticed, but these extended only a very short distance, probably because of the relatively thin total wall thickness. Evidence of initial blackening in oil spaces was also invariably noticed at the edges of the small holes in the central tubular conductor and outer lead-foil electrode drilled to facilitate drying and impregnation. However, the failure showed no preference for the edges of these holes. Invariably the central tubular conductor would be blackened under the full spiral length of the oil channel between the tape edges of the first layer, the remainder of the conductor remaining clean and bright.

Altogether the failures seem to be closely similar to those reported by Robinson[7] and Race,[8] both of whom find that the initial carbonization occurs next an electrode. However, several of our specimens have shown evidence that the initial seat of the trouble may be in the center of the insulation wall.

The interrupted failures and behavior described above are best observed in the thinner range of papers (see particularly results of the study of the influence of paper density[1]). In the present tests as the thickness increases, it is more and more difficult to limit the failure to a portion of the wall. Most of the failures above those in the three-mil paper have been through-failures with more pronounced burning, with less tendency to tree patterns and tracking and consequently with greater obscurity of the conditions surrounding initial failure.

Discussion of Results

Breakdown Strength and Life

The most probable explanation of the decrease of breakdown stress and life with increasing thickness of paper is the well-known fact that the breakdown strength of thin oil films decreases with increasing thickness. Our results indicate that the failures always start in the oil films between successive turns of paper tape. J. Sorge[9] reports a decrease of dielectric strength with increasing gap thickness, between approximately parallel planes, for xylol, benzene, and hexane, over a range of thickness 0.2 to 0.7 millimeter (8 to 28 mils). This is just outside our range of oil-channel thicknesses (3.5 to 8.0 mils). However, Sorge's curves are all pointing sharply upward at the lower values of gap. Other authors[10] report similar behavior.

Approximate computations[1] of the values of stress in the oil channels in our results in the increasing order of paper thickness are 1,506, 1,416, 1,170, 1,075 volts effective per mil. Naeher's[11] values for pure liquids and thicker layers mentioned above are from 1,700 to 1,200 volts per mil. His results on transformer oil and for gaps from 0.5 to 3 millimeters show a decrease of from 560 to 400 volts per mil. It will be seen, therefore, that our values are intermediate between those for the pure liquids of Sorge and those of Naeher for transformer oil, which was probably not so highly purified as the oil of our tests. In explanation of the above behavior, I suggest the presence of mobile ions in the oil which are greater in number with increasing thickness of oil channel. These ions, owing to the high values of their mobilities, pass to the radially opposite faces of the oil channel in a very small fraction of one-half the period of alternating 60-cycle voltage. They accumulate at the opposite faces as space charges and thus increase the potential gradient between paper and oil on either one or both of the faces of the channel. Breakdown begins at these high points of electric stress in the oil. Naturally the effect would be accentuated by minute filaments of paper projecting into the oil. With increasing thickness of the channel, more ions are present, greater values of space charge accumulate, and consequently a critical breakdown strength of the oil is reached at a lower value of over-all stress.

Dielectric Loss and Power Factor

These two quantities apparently decrease with increasing thickness of the paper, the former by about 20 per cent and the latter by about 15 per cent. The explanation is not entirely obvious. Only a portion of these decreases is accounted for by the variation in paper density. With increasing paper thickness, there are obviously fewer oil layers between paper tapes. The oil channels, however, apparently do not enter into the matter of loss in any considerable extent; first because the oil channels have the same total thickness for all thicknesses of paper; moreover, the volume of oil is a relatively small fraction of the total volume, and the loss per unit volume in oil is generally substantially less than that in the impregnated paper.

The losses in impregnated paper, qualitatively speaking, should vary in accordance with the laws for a Maxwell layer dielectric. This affords a very much better explanation of the results found. There are fewer oil layers with the thicker tapes and the barrier action to current flow is obviously greater in the thicker tapes. Thus the number of surface layers of charge at the surfaces of separation, the amount of dielectric absorption, and consequently the dielectric loss under alternating stress, are all lowered with increasing thickness of paper.

Summary and Conclusions

1. Accelerated voltage-time tests have been carried out on samples of impregnated-paper insulation with the thickness of the paper tape as a variable. Four thicknesses of nominal values, 3, 5, 6.5, and 8 mils, and all of approximately the same density, were studied. All specimens were impregnated with a very fluid insulating oil.

2. In accelerated voltage-time tests beginning at 400 volts per mil and with geometric increase of voltage at the rate of 3.12 per cent every four hours, the 60-cycle breakdown voltage was found to decrease with increasing paper thickness. Over the range of thickness mentioned, the decrease in breakdown voltage with increase of thickness was about 28 per cent. The decrease in life was approximately 45 per cent.

3. The failures almost invariably start in the oil channels between successive convolutions of the paper tape.

4. The maximum stress in the oil channels at breakdown, as computed from the dielectric constant of the oil, and the measured dielectric constant of the impregnated paper, decreased with increasing thickness over the range studied from 1,506 to 1,075 volts effective per mil. An explanation of this behavior is offered.

5. The dielectric constant of the impregnated paper is approximately constant over the range of thickness studied.

6. Power factor and dielectric loss decrease with increasing paper thickness, the former by about 30 per cent and the latter by about 20 per cent over the range of thickness studied. This behavior is explained qualitatively by the variation in interfacial polarization in accordance with Maxwell's theory.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 Supplement to Electrical Engineering—Transactions Section.

Computation of Accuracy of Current Transformers

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WHILE the general principles of the operation of current transformers have been known for some time, and tests have provided much experimental data, the introduction of high-speed relaying, especially differential protection, required a greater knowledge of current-transformer performance than was necessary previously. It is the purpose of this paper to present a method of calculating the accuracy of current transformers.

Formulas for calculating leakage flux and leakage reactance in power transformers have been available for several years. Some good experimental work showing the effect of leakage on the flux densities of the core of current transformers was done by H. W. Price and C. K. Duff of the University of Toronto, and much study has been devoted to the magnetic properties of iron and other material, but little seems to have been done in applying the formulas of power transformers to current transformers, or in establishing the rules which govern the effect of leakage flux on the accuracy. Most of the information concerning current transformers has been derived by the experimental method of making ratio correction factor and phase-angle tests of models.

However, within recent years, a considerable amount of work and testing has been done at the West Lynn Works of the General Electric Company to obtain reliable information on the exciting currents of various magnetic materials over a wide range of flux density. This information made it possible to check methods of calculating the accuracy. The method of calculation here presented was developed largely on a theoretical basis from the fundamental principles involved making use in so far as possible of the well-established power-transformer formulas and was found to give results in very good agreement with the tested accuracy.

By using the method presented in this paper it becomes possible to calculate current-transformer performance from available experimental data without making and testing models. This makes it possible to design current transformers for specific application, or determine the suitability of an existing design without the cost of overcurrent ratio and phase-angle test. It is also very useful as a tool to the designer, because it enables him to compare several proposed designs, and select the best at less cost than by using experimental models and making tests.

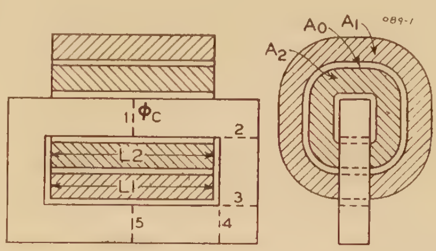

Figure 1

A_1—Area of end of primary winding as shown*
A_0—Area of space between windings as shown*
A_2—Area of end of secondary winding as shown*
L_1—Primary winding layer length*
L_2—Secondary winding layer length*
N_2—Secondary turns
Z_B—Impedance of external burden $= R_B + jX_B$
R_B—Resistance of external burden in ohms
X_B—Reactance of external burden in ohms
R_2—Resistance of secondary winding
V_2—Secondary terminal voltage
E_2—Secondary induced voltage (that is, voltage induced by mutual flux and leakage flux)
E_{L2}—Voltage induced in secondary by leakage fluxes
I_2—Secondary current in amperes
Φ_M—"Mutual flux" Φ_M will be considered to be entirely within the core (that is, it completes its circuit without entering or leaving the core)
Φ_{L2}—Secondary leakage flux (that is, flux passing through secondary copper)
Φ_{L0}—Leakage flux between windings (that is, flux passing between primary and secondary)
Φ_{L1}—Primary leakage flux (that is, flux passing through primary copper)
Φ_C—The flux in the core at the center of the secondary coil (section 1 shown in figure 1)
$j = \sqrt{-1}$
$K = 2\pi f N_2 (10^{-8})$ where $f =$ frequency

* All dimensions in inches.

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In order to compute the accuracy of a current transformer it is first necessary to define the term "accuracy". This can best be done by defining the inverse of accuracy, that is, the error. Fundamentally, the error of a current transformer is the vector difference between the primary and secondary ampere turns. Now this difference is, by virtue of the relative position of the primary and secondary coils, the number of ampere turns acting on the magnetic circuit of the transformer and is, therefore, the exciting current of the transformer in ampere turns. Hence, the rather intangible expression "accuracy" upon analysis becomes simply the inverse of exciting current.

It is, therefore, the first purpose of the following analysis to determine the exciting current. Only a wound-type transformer with two coils, one inside the other, will be considered in detail, but the general principles for the most part apply to any type.

In the development of the formulas the following assumptions will be made:

1. The secondary coil is inside the primary, which is usually the case.

2. The leakage flux flows parallel to the axis of the coil.

3. Flux density is zero on the outside of the primary copper and inside of the secondary copper, and increases linearly to the edges of the space between the copper of the two coils, the density on the primary side of the space being $3.2N_2I_2/L_1$ lines, secondary side $3.2N_2I_2/L_2$ making a mean density in the space of $3.2(2N_2I_2)/(L_1+L_2)$ all values being expressed in English units* (see figure 1 for symbols). Although it is obvious that the assumption regarding the conformation of the magnetic field is not exactly true, these assumptions are conventionally made in calculating reactance of transformers and have been shown to give values in good agreement with test.

4. In the computation of exciting current the ampere turns required for the core joints will not be considered separately. This procedure is usually permissible, if, as in the computations here presented, the core data used are derived from tests on a core having approximately the same number of joints per inch as the core of the transformer under consideration and if the joints are symmetrically disposed on the core. In some cases where the joints all happen to be in regions of flux density much higher than that in the rest of the core it may be necessary to consider the joints separately if the densities are high. This can be done by

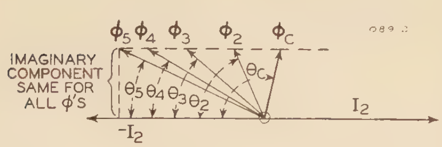

Figure 2. Phase angles between secondary current and fluxes in different sections of core

determining the density at the joints from the equations hereafter presented and adding the necessary ampere turns for the joints to the exciting ampere turns required for the rest of the core. Except on cores having short magnetic circuits or cores made of very high permeability material good lapped joints will not take a very large per cent of the total exciting current required for the core at low flux densities but usually will at high densities.

5. Much the same statement holds with respect to grain direction for cores in which the flux path is in different directions relative to the grain of the iron in different sections of the core, as the exciting current is usually higher when the flux flows across the grain than when it flows parallel to the grain.

6. The exciting currents will be treated as vectors in adding the exciting current for the various sections of the core, although it is not strictly correct to represent them as such since they are not in general sinusoidal. Experience, however, indicates that the errors introduced by assuming them so are

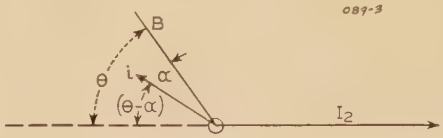

Figure 3. Vector diagram showing relation between flux density, exciting ampere turns, and secondary current for any particular core section

negligible except possibly at quite high flux densities where the wave form of the exciting current is badly distorted.

7. The magnitude of the leakage flux and its conformation are assumed to be dependent only upon the geometry of the apparatus, and the ampere turns in the coils, and are independent of the permeability of the magnetic core material. This assumption, of course, is valid only if the permeability of the core material is high relative to that of the air or other nonmagnetic media. Should the permeability of the core become quite low as the result of either a high overcurrent or a heavy burden which badly saturates the core, the configuration of the leakage flux may be altered, and its magnitude will no longer be strictly proportional to the ampere turns in the coils. This assumption limits the application of this method of analysis to conditions where the maximum magnetizing force in the core is about 300 ampere turns per inch or less.

8. It is also assumed in the analysis that with a sinusoidal primary current the secondary current will be a sine wave. For this assumption to be reasonable, it is necessary that the exciting current either be nearly sinusoidal or be a small per cent of the primary current. Actually the exciting current is almost never sinusoidal although it may be approximately so for the

* The factor 3.2 comes about as follows: For air using metric units flux density $B=H=0.4\pi NI/\text{cm}$ lines per square centimeter. Therefore, in English units $B=0.4\pi \text{NI/in.}\times 2.54$ lines per square inch.

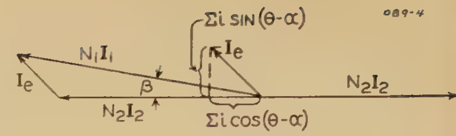

Figure 4. Vector diagram of relation between primary and secondary ampere turns and total exciting ampere turns for core of a current transformer

lower values of flux density; but it is usually, in good transformers, a small per cent of the load current. Therefore, the harmonics introduced by the exciting current are seldom of much consequence in the normal range of operation. However, here again, if due to either high overcurrent or a heavy burden, the core becomes saturated, the exciting-current wave form has large harmonics and the transformer error usually gets relatively large in which case the per cent of harmonics in the secondary current is likely to be appreciable.

If the harmonics thus introduced into the secondary current are large enough to be of concern, then a more precise and elaborate definition of accuracy is necessary as the ratio and phase-angle errors alone will no longer suffice to define completely the difference between the correct and the actual values of secondary current.

In figure 1 is shown a wound-type current transformer of a type which will be considered, and below it is a list of the principal symbols used. **Bold-face** type indicates a vector quantity, and all vectors will be referred to the secondary current as a base.

On the basis of the assumption relative to the distribution of leakage flux, the values of leakage flux are:

$$\Phi_{L_2}=3.2\frac{N_2I_2}{2L_2}A_2 \tag{1}$$

$$\Phi_{L_0}=3.2\frac{N_2I_2}{L_1+L_2}2A_0 \tag{2}$$

$$\Phi_{L_1}=3.2\frac{N_2I_2}{2L_1}A_1 \tag{3}$$

In order to determine the exciting current it is first necessary to establish the

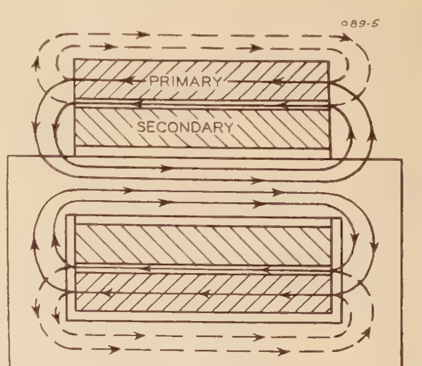

Figure 5. Paths of leakage flux which does not pass through secondary copper

flux density or densities in the core. This can most readily be done by beginning with Φ_C. To find Φ_C it will be assumed that the fraction of Φ_{L2} which returns inside the secondary is Y and that the fraction of $(\Phi_{L1}+\Phi_{L0})$ returning inside the secondary is U. The fractions Y and U are involved in the calculation of Φ_C in two ways. In the first place, it is apparent that

$$\Phi_C=\Phi_M+Y\Phi_{L2}+U(\Phi_{L1}+\Phi_{L0})$$

In the second place Φ_M is related to E_{L2} and E_2 by the relation

$$E_2=-jK\Phi_M+E_{L2}$$

whence

$$\Phi_M=\frac{j}{K}E_2-\frac{j}{K}E_{L2}$$

and it is obvious that E_{L2} will be dependent on the values of Y and U. In the appendix it is shown that

$$E_{L2}=-jKU(\Phi_{L1}+\Phi_{L0})-jK\Phi_{L2}\left(Y-\frac{1}{3}\right) \quad (4)$$

$$\therefore \Phi_M=\frac{j}{K}E_2-\frac{j}{K}\left[-jKU(\Phi_{L1}+\Phi_{L0})-jK\Phi_{L2}\left(Y-\frac{1}{3}\right)\right]$$

or

$$\Phi_M=\frac{j}{K}E_2-U(\Phi_{L1}+\Phi_{L0})-\Phi_{L2}\left(Y-\frac{1}{3}\right)$$

Substituting this value of Φ_M in the equation of Φ_C above gives

$$\Phi_C=\frac{j}{K}E_2-U(\Phi_{L1}+\Phi_{L0})-\Phi_{L2}\left(Y-\frac{1}{3}\right)+Y\Phi_{L2}+U(\Phi_{L1}+\Phi_{L0})$$

$$\therefore \Phi_C=\frac{j}{K}E_2+\frac{1}{3}\Phi_{L2} \quad (5)$$

It is, therefore, evident that it makes no difference in the value of Φ_C what assumptions are made regarding the return of the leakage flux since neither Y nor U occurs in the expression for Φ_C.

Referring to the last equation since Φ_{L2} has already been expressed in terms of I_2 (equation 1), it is now necessary to determine E_2 in terms of I_2. This is readily accomplished by adding the internal secondary IR drop to the secondary terminal voltage since E_2 by definition is the net voltage induced by all fluxes including leakage.

$$\therefore E_2=V_2+I_2R_2$$

but

$$V_2=I_2R_B+jI_2X_B$$
$$\therefore E_2=I_2(R_2+R_B)+jI_2X_B$$

Substituting in equation 5 this value of E_2 and the value of Φ_{L2} given in equation 1 in terms of I_2 gives

$$\Phi_C=I_2\left[\frac{j}{K}(R_B+R_2)\right]+\frac{j}{K}(jI_2X_B)+\frac{1}{3}\left(3.2\frac{N_2I_2}{2L_2}A_2\right)$$

or

$$\Phi_C=I_2\left[\frac{j}{K}(R_B+R_2)-\frac{X_B}{K}+.533\frac{N_2A_2}{L_2}\right] \quad (6)$$

To determine the fluxes at other points in the core it is necessary to know how much of the leakage enters the core between various points in its length. In general, it can be assumed that all the leakage flux which passes through and between the copper inside the core window enters the core. Of the remainder about 50 per cent will enter the core between sections 1 and 5.

If Φ_{LT} = flux entering the core between sections 1 and 5,

$$\Phi_{LT}=(\Phi_{L1}+\Phi_{L0}+\Phi_{L2})\times\left[\frac{h}{MLT_0}+\frac{1}{2}\left(1-\frac{h}{MLT_0}\right)\right]$$

Where h = height of core in the case of a "core" type core or twice the height in the case of a shell-type core and MLT_0 = mean length in the direction of the windings around the space between the windings

$$\therefore \Phi_{LT}=\left(\frac{\Phi_{L1}+\Phi_{L0}+\Phi_{L2}}{2}\right)\left(1+\frac{h}{MLT_0}\right)$$

Of Φ_{LT} a certain fraction, K_1 will enter the core between sections 1 and 2, another fraction, K_2, will enter between 1 and 3, and another fraction, K_3, between 1 and 4. The values of K_1, K_2, K_3, will be usually in the neighborhood of 0.57, 0.87, and 0.93 respectively. With these values of leakage flux entering the core the values of flux at the sections 2, 3, 4, and 5 will be given as follows, the subscripts after the Φ denoting the section:

$$\Phi_2=\Phi_C-K_1\Phi_{LT}=I_2\left[\frac{j}{K}(R_B+R_2)-\frac{X_B}{K}+\frac{0.533N_2A_2}{L_2}\right]-K_1\Phi_{LT} \quad (7)$$

$$\Phi_3=\Phi_C-K_2\Phi_{LT}=I_2\left[\frac{j}{K}(R_B+R_2)-\frac{X_B}{K}+\frac{0.533N_2A_2}{L_2}\right]-K_2\Phi_{LT} \quad (8)$$

$$\Phi_4=\Phi_C-K_3\Phi_{LT}=I_2\left[\frac{j}{K}(R_B+R_2)-\frac{X_B}{K}+\frac{0.533N_2A_2}{L_2}\right]-K_3\Phi_{LT} \quad (9)$$

$$\Phi_5=\Phi_C-\Phi_{LT}=I_2\left[\frac{j}{K}(R_B+R_2)-\frac{X_B}{K}+\frac{0.533N_2A_2}{L_2}\right]-\Phi_{LT} \quad (10)$$

The flux densities, β_C, β_2, β_3, β_4, and β_5 corresponding to the fluxes Φ_C, Φ_2, Φ_3, Φ_4, and Φ_5 are, of course, the absolute values of these fluxes divided by the cross-sectional areas of the core at the respective points, and the sines of the angles θ_C, θ_2, θ_3, θ_4, and θ_5 between β_C, β_2, β_3, β_4, and β_5 respectively and the secondary current reversed are the imaginary components of the fluxes divided by the absolute values (see figure 2). It should be noted that θ_C may be greater than 90 degrees.

If α_C, α_2, α_3, α_4, and α_5 (figure 3) are the angles between the flux densities and

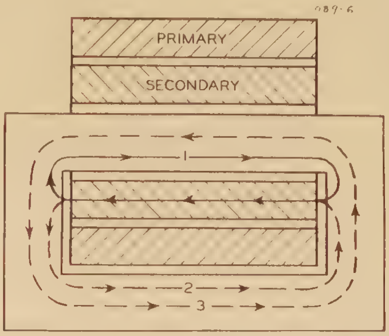

Figure 6. Paths of leakage flux which does pass through secondary copper

their respective unit values of exciting ampere turns* i_C, i_2, i_3, i_4, and i_5, as determined from magnetization data on the iron, then by averaging the values for each section of length the components of exciting ampere turns in phase with the secondary current reversed will be:

$$\frac{L_{12}}{2}[i_C\cos(\theta_C-\alpha_C)+i_2\cos(\theta_2-\alpha_2)] \quad \text{for section 1–2}$$

$$\frac{L_{23}}{2}[i_2\cos(\theta_2-\alpha_2)+i_3\cos(\theta_3-\alpha_3)] \quad \text{for section 2–3}$$

$$\frac{L_{34}}{2}[i_3\cos(\theta_3-\alpha_3)+i_4\cos(\theta_4-\alpha_4)] \quad \text{for section 3–4}$$

$$\frac{L_{45}}{2}[i_4\cos(\theta_4-\alpha_4)+i_5\cos(\theta_5-\alpha_5)] \quad \text{for section 4–5}$$

Where the L's represent the lengths between the sections denoted by the subscripts. Since there are two of each of the above sections in the whole core the total component of exciting ampere turns in phase with the secondary current reversed will be given by

$$\Sigma i\cos(\theta-\alpha)=L_{12}i_C\cos(\theta_C-\alpha_C)+(L_{12}+L_{23})i_2\cos(\theta_2-\alpha_2)+(L_{23}+L_{34})i_3\cos(\theta_3-\alpha_3)+(L_{34}+L_{45})i_4\cos(\theta_4-\alpha_4)+L_{45}i_5\cos(\theta_5-\alpha_5)$$

Similarly the component of exciting am-

* These quantities here represent actual ampere turns per inch.

Table I. Core Flux

Section	Measured	Calculated
Transformer No. 1 — Secondary amperes = 4.89; Burden = 0.533 ohm R and 0.878 ohm X; Volts per turn referred to secondary current		
1	$0.0158+j0.0052$	$0.0152+j0.0067$
2		$0.0152+j0.038$
3		$0.0152+j0.055$
4	$0.0165+j0.0538$	$0.0152+j0.059$
5	$0.0164+j0.0583$	$0.0152+j0.063$
Transformer No. 2 — Secondary short-circuited; Secondary amperes = 4.89; Volts per turn referred to secondary current		
1		$0.0065-j0.0076$
2	$0.0064+j0.0315$	$0.0065+j0.035$
3	$0.0063+j0.057$	$0.0065+j0.058$
4	$0.0066+j0.061$	$0.0065+j0.062$
5	$0.0075+j0.064$	$0.0065+j0.067$
Transformer No. 3 — Secondary short-circuited; Secondary amperes = 4.85; Volts per turn referred to secondary current	Measured*	
1		$0.0058-j0.0033$
2	$0.00616+j0.0064$	$0.0058+j0.0064$
3	$0.00630+j0.0113$	$0.0058+j0.0115$
4	$0.00640+j0.0125$	$0.0058+j0.0127$
5	$0.00656+j0.0144$	$0.0058+j0.0138$

*Values are average of values obtained on two transformers. Samples differed by almost 20 per cent.

Transformer number 1—General Electric type *KF*-85.

Transformer number 2—General Electric type *KF*-58.

Transformer number 3—General Electric type *WF*-12.

pere turns 90 degrees out of phase with the secondary current is given by

$$\Sigma i \sin(\theta-\alpha)=L_{12}i_C \sin(\theta_C-\alpha_C)+(L_{12}+L_{23})i_2\sin(\theta_2-\alpha_2)+(L_{23}+L_{34})i_3\sin(\theta_3-\alpha_3)+(L_{34}+L_{45})i_4\sin(\theta_4-\alpha_4)+L_{45}i_5\sin(\theta_5-\alpha_5)$$

Since these components of exciting ampere turns must be added to the secondary ampere turns reversed to obtain the primary ampere turns the latter are given by

$$N_1I_1=-N_2I_2-\Sigma i\cos(\theta-\alpha)+j\Sigma i\sin(\theta-\alpha)$$

as shown in figure 4.

Therefore, ratio correction factor is†

$$RCF=\sqrt{\left[1+\frac{\Sigma i\cos(\theta-\alpha)}{N_2I_2}\right]^2+\left[\frac{\Sigma i\sin(\theta-\alpha)}{N_2I_2}\right]^2}$$

and the phase angle is

$$\beta=\sin^{-1}\frac{\Sigma i\sin(\theta-\alpha)}{N_1I_1}$$

If the common method of compensating by changing secondary turns is employed this percentage, of course, must be subtracted from the value computed above.

† This equation for ratio correction factor, of course, applies only to uncompensated transformers.

Other special methods of compensation require special calculations of their own to compute the final accuracy, although it is usually necessary to compute the uncompensated accuracy first in any event.

Discussion and Review

An inspection of the results of the analysis reveals some interesting facts. In the first place equations 6 to 10 inclusive show that the component of flux 90 degrees out of phase with the secondary current is the same in all sections of the core.

Actually this is not strictly true as in transformers having large primary conductors the eddy currents tend to make the leakage flux lag the primary current so that a component of the leakage shows up 90 degrees out of phase with the primary and secondary turns. The magnitude of this component of the leakage flux however, is almost always quite small compared to the average value of total flux in the core as shown by table I.

Equations 6 and 10 show that if the external burden and internal resistance are small Φ_C and Φ_5 may be almost 180 degrees apart. This may seem unreasonable but actual flux measurements on the core show it to be true.

It will be noticed that no mention has been made of secondary reactance. The term was not used because it necessitates defining a rather elusive quantity which is not of any particular value in solving the problem. The term is elusive and confusing because reactance, being volts divided by amperes, depends on the voltage induced by the secondary leakage flux which, as has been seen, depends on the direction of return of this leakage. Moreover, the secondary leakage flux, Φ_{L2} must return outside the secondary coil if the in-phase component of Φ_C is negative, as is generally the case (see equation 6), because if one is to adhere strictly to physical realities there cannot be flux flowing in opposite directions in the same section of the core at the same instant. If Φ_{L2} does all return outside the secondary, the voltage generated is positive and hence the reactance must be negative. If, on the other hand, the in-phase component of Φ_C is $+{}^1/_3\ \Phi_{L2}$, the maximum value without leading power factor burden, then ${}^1/_3\ \Phi_{L2}$ returns inside the secondary. Referring to equation 4 this means $Y={}^1/_3$ and hence the voltage induced by the secondary leakage flux equals zero. Therefore, if reactance is to be defined in the conventional manner and the flux paths are to be taken exactly as they are, the only conclusion is that the secondary reactance is a variable depending on the external burden and varying between zero and $-K\Phi_{L2}/3I_2$. It is consequently evident that the use of the term "secondary reactance" is of no advantage in this analysis, as a rigorous definition of such a term makes it necessary to solve most of the problem to determine the reactance.

Tables I, II, and III give comparisons of calculated and measured results. Transformers numbers 1 and 2 were different in size but of similar design while the proportions of transformer number 3 were considerably different from the first two. An inspection of the tabulated values shows that there is still some room for improvement in the accuracy of the calculations which further study and added refinements might produce. On the other hand, the discrepancies between the calculated and the measured values of flux are no greater than the errors frequently incurred in computing the physical dimensions of the coils and the space between them. In fact, to go even further, tests show that in some cases the variation between individual samples of the same design is greater than the error of the calculations. Moreover, both tests and simple computation show that what appears to be a small degree of dissymmetry in the coils will frequently cause a large difference between the values of flux in the opposite ends of the core. From a practical point of view, therefore, further refinement in the method of calculating the flux will not produce the improvement in over-all results which would be expected at first glance.

Moreover, any such refinements in the calculations would be largely a matter of field theory in determining the exact conformation of the leakage flux outside the core rather than any alteration of the principle involved and in the writer's

Table II

Transformer Number 1—Leakage Fluxes, Secondary Short-Circuited; Secondary Amperes = 5.0

	Crest Values of Flux	
	Measured	Calculated
Φ_{L2}	9,450	8,750
$\Phi_{L0}+\Phi_{L1}$	25,650	28,000
$\Phi_{L1}+\Phi_{L0}+\Phi_{L2}$	35,100	36,800
Negative flux at center of secondary	3,490	2,920
Flux in item above divided by Φ_{L2}	0.37	0.33
Φ_{LT}	20,270	21,500
$\left[\dfrac{\Phi_{LT}}{\Phi_{L0}+\Phi_{L1}+\Phi_{L2}}\right]$	0.578	0.585

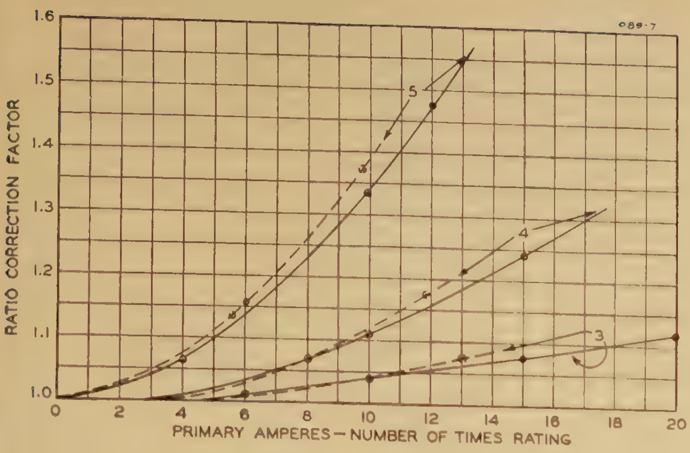

Figure 7. Overcurrent accuracy, transformer number 2 (see table I)

Burdens (volt-amperes based on five amperes):
3—50 volt-amperes, 50 per cent power factor
4—100 volt-amperes, 50 per cent power factor
5—200 volt-amperes, 50 per cent power factor
Solid curves—Test values
Dashed curves—Calculated values

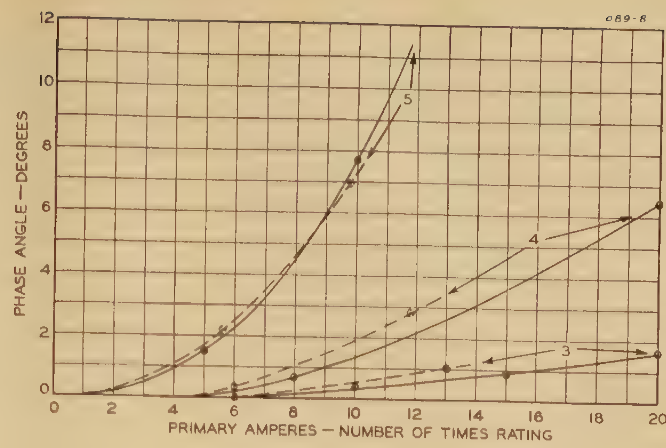

Figure 8. Overcurrent accuracy, transformer number 2 (see table I)

Burdens (volt-amperes based on five amperes):
3—50 volt-amperes, 50 per cent power factor
4—100 volt-amperes, 50 per cent power factor
5—200 volt-amperes, 50 per cent power factor
Solid curves—Test values
Dashed curves—Calculated values

opinion the chief value in the foregoing analysis is the establishment of the general theorem by which the flux densities in the core can be determined from a given conformation of leakage flux, ampere turns, secondary burden, etc. A concrete illustration of this statement is afforded by the bar or through-type transformer having a single primary turn. In this type the magnetic field is altogether different from the wound type, and a totally different method of evaluating the leakage flux must be used, but having established the values of leakage flux entering the core the method of determining the flux densities in the core is exactly the same as with the wound type. In passing it might be mentioned that in the case of high-current bar or through-type transformers, particularly those with only two secondary coils, the leakage flux is generally of much more importance than in other designs.

A detailed discussion of a precise definition of accuracy including the effects of wave-form errors is beyond the scope of this paper, but since the exciting current is responsible for the added complications of harmonics the subject of wave form should not be passed over without mentioning the importance of the method of making exciting-current tests. At high flux densities in magnetic cores harmonics become a large per cent of the effective values of voltage or current or both depending on the test setup, and results may vary over a wide range depending on the wave form of voltage applied and the methods of measurement. On the basis of both experience and theoretical considerations, in the writer's opinion, the most satisfactory method of making exciting-current tests for current-transformer accuracy calculations is to apply a sine-wave voltage to a coil of low resistance wound on the core, and measure both the current and the voltage with an instrument such as a vibration galvanometer or separately excited dynamometer instrument which will give the fundamental components of the voltage and current waves. For tests at very high density the actual transformer coils and core should be used, the exciting current being applied to the primary coil and the voltage measured on the secondary.

While the method of calculation here presented is subject to the limitations implied in the assumptions and discussed previously, it can be used with reasonably good results for the calculation of overcurrent accuracy up to a current where the maximum magnetizing force in the core is about 300 ampere turns per inch. For many cases this will be high enough. Curves, figures 7 and 8, show results that may be expected up to limit specified. On some transformer designs which by virtue of their geometry have no leakage entering the core, the flux density in the magnetic circuit is uniform throughout its length. In such cases, the overcurrent calculations can be carried out successfully above the limit specified above.

With regard to the practical value of the method of calculation here presented, the method is quite useful in designing transformers to meet special requirements or specifications. It is also valuable in comparing the worth of proposed designs, and its value in this respect is enhanced by the fact that to test such proposed designs it is necessary to make several samples on account of the uncertainty with most core materials in obtaining a representative core in any particular sample. Another value in the method of calculating the accuracy is to be able to compare the relative advantages of different core materials in a given design, where again, if actual tests are made a number of cores will usually have to be tried before a representative sample is obtained. However, in this case where

Table III. Accuracy (Without Wilson Compensation)

Transformer Number	Burden (Ohms)	Secondary Amperes	Measured Values: Ratio Correction Factor	Measured Values: Phase Angle (Minutes)	Calculated Values: Ratio Correction Factor	Calculated Values: Phase Angle (Minutes)
1	$R=0.24$, $X=0$	0.5	0.9994	5	1.0002	4
		5	0.9961	0.5	0.9964	0
	$R=0.98$, $X=1.53$	0.5	1.0043	7	1.0050	6.5
		5	0.9979	−0.5	0.9983	−1
3	$R=0.24$, $X=0$	0.5	1.0054	17	1.0059	17
		5	1.0030	6	1.0029	6
	$R=0.98$, $X=1.53$	0.5	1.0158	17	1.0165	17
		5	1.0064	1	1.0070	1

transformers are probably available it is almost as quick and more accurate to make measurements of flux in the core, thereby eliminating that much computation. If data are then available on the materials to be considered, the accuracy can be computed from these data and the flux measurements.

Moreover, since considerable equipment and expense are involved in making overcurrent accuracy tests, it is, of course, quite valuable to be able to calculate the performance at high currents particularly in designing apparatus for special requirements when there is usually not time to build and test samples.

Appendix

Voltage Induced by Leakage Flux in Secondary; Proof of Equation 4

In verifying equation 4, first consider the leakage $(\Phi_{L0}+\Phi_{L1})$ figure 5. Since all this flux in traversing the space occupied by the coils passes outside the secondary copper, all that returns along the paths represented by the solid lines links all the secondary turns and all that returns along the dotted paths links no secondary turns. Hence, the voltage induced by the amount that returns outside the secondary will be zero and that which returns inside the secondary coil will generate a voltage equal to $2\pi f N_2 \cdot 10^{-8} U(\Phi_{L0}+\Phi_{L1})$ since U is by hypothesis the fraction returning inside the secondary. Also, since $U(\Phi_{L0}+\Phi_{L1})$ is in phase with the secondary magnetomotive force the voltage generated is $-jKU(\Phi_{L0}+\Phi_{L1})$ referred to the secondary current.

To determine the voltage generated by Φ_{L2} consider any one particular line of flux as shown in figure 6. Let the fraction of the secondary turns between this line of flux and the inside of the secondary coil equal S. If the line of flux returns along the path number 1, the voltage generated is $-jKS$. If, on the other hand, the line of flux returns along path number 2, the voltage is $+jK(1-S)$. The algebraic difference, $jK(1-S)-(-jKS)$ is readily seen to be jK. Hence, the difference in generated voltage obtained by changing the return of the flux line from path number 1 to path number 2 is jK and is the same as the voltage generated by a line following path number 3. But the flux line considered is any line passing through the secondary copper, and, therefore, the result must be true for all such lines. Consequently, the voltage difference due to changing the paths of N such lines from inside to outside is jKN. Therefore, if the voltage generated by assuming all Φ_{L2} returns along path number 1 is E_0, the voltage E_A, generated when $(1-Y)\Phi_{L2}$ lines return along path number 2 is $E_A=E_0+jK(1-Y)\Phi_{L2}$ where Y is, of course, the fraction of Φ_{L2} returning inside the secondary as assumed in equation 4.

It can be shown* that if d_4 = the mean radius of the inside of the secondary coil (that is, $1/2\pi$ times the length at the inside turn) and d_2 = the thickness of winding in inches, the voltage E_0 is given by the equation

$$E_0=-j2\pi f\left\{\frac{0.8\pi^2 N_2^2 I^2}{L_2}\left[\frac{d_4 d_2}{3}+\frac{d_2^2}{4}\right]\right\}\times (2.54)10^{-8}$$

the 2.54 being the factor to change the formula from centimeters to inches.

$$\therefore E_0=-jK\left(\frac{6.4N_2I_2}{L_2}\right)\left[\frac{d_4d_2}{3}+\frac{d_2^2}{4}\right](\pi)$$

and

$$\Phi_{L2}=\frac{6.4N_2I_2}{L_2}\left[\frac{d_4d_2}{2}+\frac{d_2^2}{3}\right](\pi) \qquad (11)$$

$$\therefore \frac{E_0}{\Phi_{L2}}=-jK\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right)$$

or

$$E_0=-jK\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right)\Phi_{L2}$$

$$E_A=-jK\Phi_{L2}\left[\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right)+Y-1\right]$$

since

$$E_A=E_0+jK(1-Y)\Phi_{L2}$$

or

$$E_A=-jK\Phi_{L2}\left[Y-\left\{1-\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right)\right\}\right]$$

if

$$\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right) \qquad (12)$$

is set equal to q and m equal to $(1-q)$, then

$$E_A=-jK\Phi_{L2}[Y-m] \qquad (13)$$

It is evident that q will be between $2/3$ and $3/4$. As a matter of fact, it will be generally very nearly $2/3$ making m very nearly $1/3$. It can, moreover, be shown that the value of $m\Phi_{L2}$ is exactly the same if Φ_{L2} is calculated as shown in equation 1 and m is taken equal to $1/3$ as it is if m and Φ_{L2} are computed as shown in formulas 11 and 12.

Using the latter combination it is seen that

$$m\Phi_{L2}=(1-q)\Phi_{L2}=\left[1-\left(\frac{\frac{d_4}{3}+\frac{d_2}{4}}{\frac{d_4}{2}+\frac{d_2}{3}}\right)\right]\times \left[6.4\pi\frac{N_2I_2}{L_2}d_2\left(\frac{d_4}{2}+\frac{d_2}{3}\right)\right]$$

$$m\Phi_{L2}=6.4\pi\frac{N_2I_2}{L_2}d_2\left(\frac{d_4}{2}+\frac{d_2}{3}-\frac{d_4}{3}-\frac{d_2}{4}\right)$$

$$m\Phi_{L2}=6.4\pi\frac{N_2I_2}{L_2}d_2\left(\frac{d_4}{6}+\frac{d_2}{12}\right)$$

whereas if Φ_{L2} is computed as in equation 1

$$\Phi_{L2}=\frac{3.2N_2I_2}{2L_2}\left[2\pi\left(d_4+\frac{d_2}{2}\right)d_2\right]$$

$$\Phi_{L2}=\frac{3.2N_2I_2}{L_2}\pi d_2\left(d_4+\frac{d_2}{2}\right)$$

$$=\frac{6.4\pi N_2I_2}{L_2}d_2\left(\frac{d_4}{2}+\frac{d_2}{4}\right)$$

$$\therefore \frac{1}{3}\Phi_{L2}=6.4\pi\frac{N_2I_2}{L_2}d_2\left(\frac{d_4}{6}+\frac{d_2}{12}\right)$$

which is exactly the same as the value of $m\Phi_{L2}$ above.

While the method of calculating Φ_{L2} as given in equation 1 gives a slightly lower value than that of equation 11 the value of Φ_{L1} is higher so that the total leakage $(\Phi_{L2}+\Phi_{L0}+\Phi_{L1})$ is practically the same either way; and equations 1, 2, and 3 are somewhat simpler to use.

Therefore, using the latter formulas for the leakage fluxes and taking $m=1/3$ it is evident from quotation 13 that

$$E_A=-jK\Phi_{L2}(Y-1/3)$$

Now the voltage generated by the leakage fluxes, E_{L2} has two parts, one, that generated by Φ_{L0} and Φ_{L1} shown in the first part of the appendix to be $-jK(\Phi_{L0}+\Phi_{L1})U$ and second, the part generated by Φ_{L2} which is E_A

$$\therefore E_{L2}=-jKU(\Phi_{L0}+\Phi_{L1})-jK\Phi_{L2}(Y-1/3)$$

This relation is readily seen to be equation 4 given previously.

* See "Principles of Alternating-Current Machinery" by Ralph R. Lawrence, second edition, pages 188 and 189.

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 Supplement to Electrical Engineering—Transactions Section.

Reference Values for Temperature, Pressure, and Humidity

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IN most engineering measurements the readings obtained at a given time depend upon a number of conditions, such as temperature and barometric pressure, existing at the time of the test. In some cases the effects are very small, compared to the accuracy desired in the result, and can be neglected. In other cases prevailing conditions have a decided effect on the numerical values of the test results. For instance, in a determination of the boiling point of water, it is very necessary to consider the barometric pressure. In measuring the flashover voltage of an insulator, the temperature, pressure, and humidity each has a measurable effect on the observed value. Therefore, it has become necessary to select standard conditions to which certain measurements may be referred. This permits measurements made in different laboratories or at different times in the same laboratory to be compared directly. Certain values have been chosen, such as 760 millimeters barometric pressure, to which measurements for any physical or electrical quantity usually are referred, regardless of where in the world a particular measurement is made. This is a very convenient practice and greatly simplifies comparisons and use of engineering data.

It is therefore proposed to consider reference values for the temperature, the atmospheric pressure, and the humidity of the air. Because of their influence on measurements and on the rating of apparatus, the effects of these conditions have been analyzed. Reference values have been selected and correction factors for nonstandard conditions determined by interested standardizing groups. Certain values have been chosen as reference values because of average conditions prevailing at the time original tests were made or because of ease in maintaining a certain condition. A review of current practices indicates that 20 degrees centigrade is a favored reference value for physical and chemical quantities in both United States and international use. On the other hand 25 degrees centigrade is deeply rooted in American electrical practice. The agreement on a barometric pressure of 760 millimeters is universal. With respect to humidity, there is not much consistency in the reference values used or in the units in which they are specified. Humidity is important in fewer cases and its effects have been appreciated and evaluated more recently.

At times there is little advantage in the use of one reference value over another and, lacking organized co-ordination, slightly different values have been introduced in various standards. Although it may be impractical to remedy this undesirable condition in all cases, it is hoped that the information collected here will help to avoid further complication by minimizing the reference values adopted in future standards.

From an engineering point of view there are two types of reference values; in one case the value is of the nature of an average to which values obtained throughout a range of conditions may be referred or corrected. In the second case the problem is one of maximum values rather than average. This condition occurs notably in connection with the thermal limits and therefore the rating of electrical machinery. For rating purposes, the engineer is interested principally in ambient temperatures exceeding certain values and the time during which they prevail. The ambient-tem-

Table I. Reference Temperatures for Physical Quantities*

Quantity	United States Preferred Reference Temperature (Deg)	International Preferred Reference Temperature (Deg)
Resistivity (Cu)	20C	20C
Conductivity (Cu)	20C	20C
Temperature coefficient of resistance (Cu)	20C	20C
Specific gravity (Cu)	20C	20C
Resistivity (metals)	20C	20C
Conductivity (metals)	20C	20C
Temperature coefficient of resistance (metals)	20C	20C
Specific gravity (metals)	20C	20C
Cross section (metals)	20C	20C
Surface resistivity (dielectrics)	18–25C	18–25C
Volume resistivity (dielectrics)	20C	20C
Conductivity (dielectrics)	20C	20C
Coefficient of linear expansion	20C	20C
Coefficient of cubical expansion	20C	20C
Meter length	0C	0C
Gas volume	0C	0C
Gas density	0C	0C
Air density	0, 15, 15.5C	15, 15.5C
15-degree calorie	15C	15C
British thermal unit	60F, 39F	60F, 39F
Thermal conductivity of air	0C	0C
Coefficient of thermal expansion	20C (Ranges)	20C (Ranges)
Density (Hg)	0C	0C
Density (H_2O)	4C	4C
Density (calcite)	20C	20C
Specific gravity (oils)	15/4C	20/4C
Weights (mass)	0C	0C
Refractive index (liquids)	20C	25C−18C
Refractive index (air)	15C	15C
Cold junction of thermocouples	0C	0C
Standard cell (Weston)	20C	20C
Standard cell (Clark)	15C	15C
Barometers (reference temperature)	0C	0C
Translational energy of molecule	0C	0C
Angstrom unit (wave length)	15C	15C
Range and velocity of alpha rays	0C	0C
Mobility of ions in gases	0C	0C
Resistance of international ohm	0C	0C
Contact potentials	15–25C	
Gauges for metal fits (ASA)	20C	
Ball and roller bearings (ASA)	20C	

*Smithsonian Physical Tables, Smithsonian Meteorological Tables, Chemical Handbook, Marks Mechanical Engineers Handbook, Penders Handbook, International Critical Tables, Physical and Chemical Tables (German).

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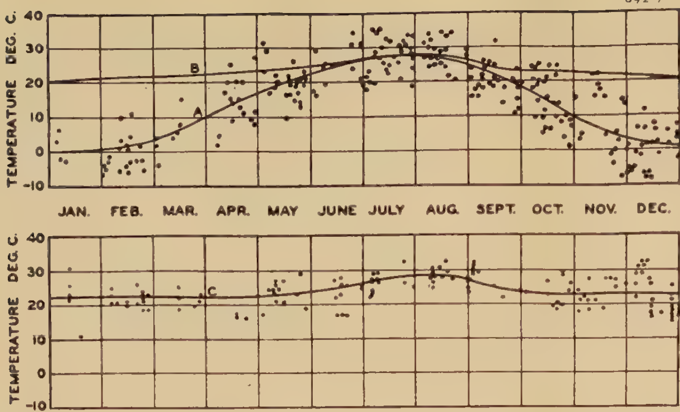

Figure 1

A—The temperatures at which high-voltage impulse tests were made outdoors at Sharon, 1936–38

B—The monthly average temperature curve indoors at Sharon, 1936–37

C—The temperatures at which high-voltage tests were made indoors at Trafford, 1936–39

perature considerations which determine apparatus rating are covered elsewhere,[5,12] notably in AIEE Standard No. 1.

In choosing and correcting to standard reference conditions, simplicity of the method is very desirable. Therefore, the reference value should be selected to represent approximately average actual conditions and to make the correction process as simple as possible. In this connection, the background and development of present standard reference conditions are discussed. Furthermore, the importance of dependable correction factors to convert performance data to the reference conditions is considered.

Temperature

(A). Reference Values

Certain specific values in connection with temperature are easily determined from well-known physical characteristics. The freezing and boiling points of water are examples. Another value is the point of maximum density of water at four degrees centigrade. In the beginning, the temperatures, at which measured quantities are given, depended upon the ease of obtaining certain temperature conditions. As progress was made the desirability of using a single or fewer reference temperatures became apparent. Table I shows some of the reference temperatures for physical and chemical quantities in United States and international use. These values were taken more or less at random from a number of standard handbooks and engineering tables. It is apparent from this table that 0 and 20 degrees centigrade are the reference temperatures now in most common use for such quantities.

Another common reference value which has been adopted, particularly for electrical-engineering use in this country, is 25 degrees centigrade. This value was established as the reference for testing apparatus. In the report of the standards committee and in companion papers presented at the 1913 AIEE midwinter symposium on standardization and apparatus rating,[1] the following parts sum up essentially the basis and reasons recognized at that time for selecting the 25-degree-centigrade value:

"The reference temperature in the guarantees should, therefore, be such as can easily be secured; that is, it should be the average temperature of the places at which the apparatus may be operated. This is from 20 degrees centigrade to 25 degrees centigrade and, as it is easier to raise than to lower the room temperature, the upper figure is advisable as a reference value. This reference temperature, therefore, should be chosen as 25 degrees centigrade, which is in accordance with the previous AIEE standard."

"It is, therefore, recommended . . . that all measurements and tests of electrical apparatus be based on a room temperature of 25 degrees centigrade."

At this same time, Chubb and Fortescue presented calibration data for the 25-, 37.5-, and 50-centimeter sphere gaps.[2] Although temperature and barometric pressure are not mentioned in their article, it is apparent from the discussions that the effect of these conditions was appreciated. The correction formula in use today for temperature and pressure was given by Peek in his discussion. The foregoing explains the use of 25 degrees centigrade in sphere-gap calibration tables in AIEE standards.[4] The use of this temperature has of course grown and for the past ten years, all high-voltage measurements have been referred to this temperature.

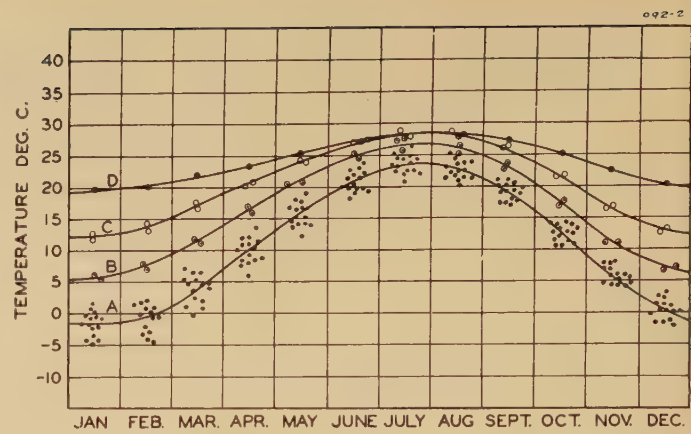

Figure 2. The average temperature curves for various regions in the United States (table IV)

A—Locations 1–15
B—Locations 16–17
C—Locations 18–19
D—Location 20

The present status of reference values in the electrical field is summed up in table III. In general, 25 degrees centigrade is the reference temperature specified for tests and test data on electrical apparatus in AIEE and ASA standards. On the other hand, AIEE standard on conductors refers to the 20-degree-centigrade temperature. International Electrotechnical Commission Standards[3] on high-voltage practice, insulators, and conductors are based on 20 degrees centigrade.

The American Society for Testing Materials has standardized a wide variety of electrical-insulating material tests for many of which temperature and humidity are important. Table II gives the reference values and specified testing ranges for a number of ASTM standards. This group has recognized the situation for some time and are aiming at a reference value of 25 degrees centigrade where possible.

(B). Temperature Conditions

For proper selection of reference values, the conditions of location of test as well as location of use are of interest. Therefore it should be useful, at this time, to consider the merits of different reference temperatures in the light of actual conditions recorded over a period of years at typical industrial establishments and of the values reported in the climatic summary of the United States Weather Bureau.[6]

(*a*). *Outdoor Use and Laboratories.* Figure 1*A* shows temperature readings over a period of several years at the Sharon, Pa., high-voltage laboratory of the Westinghouse Electric and Manufacturing Company, recorded in the course of commercial and

5. For all numbered references, see list at end of paper.

development testing of station apparatus. At this laboratory, tests on apparatus were made outdoors and the values shown, therefore, represent outdoor, daytime temperatures for Sharon. The range in temperature is from −9 degrees centigrade to 36 degrees centigrade, a total spread of 45 degrees centigrade. The annual average is about 15 degrees centigrade. The April–September average is about 24 degrees centigrade and during the winter months close to 0 degrees centigrade.

A detailed survey of these data plotted in figure 1*A* reveals that temperature variations during the day may affect the air density three to four per cent and even more from one day to the next. These variations are clearly apparent from figure 3, in which the daily maximum and minimum temperatures for Sharon covering the 24 hours during 1936 are given. Daily maximum variations frequently are 10 degrees centigrade, occasionally 15 degrees centigrade, and even more during marked changes in the atmospheric conditions. From similar charts, the annual average temperature during 1936–38 is 9.6 degrees centigrade, a value substantially lower than the 15 degrees centigrade annual average for figure 1*A*, since the former covers the full 24 hours of the day and thus includes the lower temperatures of the night. The chart for 1936 (figure 3) is of further particular interest as it shows a maximum peak temperature close to 41 degrees centigrade (July) and a minimum peak of −26 degrees centigrade (January), both of which, however, were sustained for a relatively short time. The spread between the more sustained maximum and minimum peak values is 60 degrees centigrade, to which there corresponds then a total air-density change of 22 per cent.

The climatic summary of the United States Weather Bureau gives data on temperatures that have been recorded at numerous stations located throughout the entire country. Average temperatures for 24 typical locations are listed in table IV. Locations 1 to 15 are distributed in the hot-summer and cold-winter region. This is the northeastern region between 38 degrees north and 45 degrees north latitude, which extends from approximately 105 degrees west longitude to the Atlantic Seaboard. In this region are located some three-quarters of the population and the major activities of the country. Curve *A* of figure 2 gives the temperature curve for this region as determined from these representative locations. Curve *B* is for two locations at approximately 34 degrees north latitude and curve *C* for two other locations on the 30 degrees north latitude. These curves clearly bring out the change in temperature cycle from north to south, that is, from the hot-summer and cold-winter region into the hot-summer and mild-winter region. Curve *D* is for the extreme southern fringe of the country. Due to the moderating meteorological influences on the Pacific Coast, the temperature for locations 21 to 24 (table IV) are more uniform than at corresponding latitudes in the east. For the northeastern region, the annual average (curve *A* of figure 2) is 11 degrees centigrade; the May-to-August average is 20.8 degrees centigrade. For the southeastern region, the annual average (curves *B* and *C*) is 18.7 degrees centigrade and the May-to-August average, 25.9 degrees centigrade. The annual average for the entire United States over a period of 50 years is 12.7 degrees centigrade.

In addition, the climatic summary gives the average maximum and minimum temperatures. These two limits vary from the average an amount depending on the location. For Pittsburgh which is an "average" location in the northeastern region, the spread of the average maximum and minimum temperatures from the annual average curve is about five degrees centigrade for practically the entire year. Much larger daily variations can occur as it is clearly shown in figure 3. The average temperatures for Sharon, Trafford, and East Pittsburgh come within one to two degrees centigrade of the Pittsburgh values (location 8 in table IV). It is apparent then that the temperature data recorded indoors and outdoors in testing apparatus, which are presented and discussed in this paper, are quite typical of conditions[12] that are expected elsewhere in the northeastern section of the country.

(*b*). *Typical of Large Factory Buildings, Machine Test Floors, and Large Laboratories.* Figure 1*C* shows temperature conditions for a period of years at the Trafford high-voltage laboratory. Here the testing is done indoors although the building is not well insulated and there are many places around doors which are not tight. It is seen that the average temperature throughout the year is around 23 degrees centigrade. This is very close to the standard temperature to which corrections are made. The variations in temperature measurements in this heated building are due to the high temperature gradient from floor to ceiling and represent conditions that generally are encountered in high-voltage laboratories. The distance from the floor to the roof is 65 feet and at times the gradient may reach 0.5 degree centigrade per foot. The temperature values shown in the figure were taken for all kinds of tests, but usually at the level at the apparatus being tested. For a rod gap on the floor, the temperature was measured 3 to 4 feet

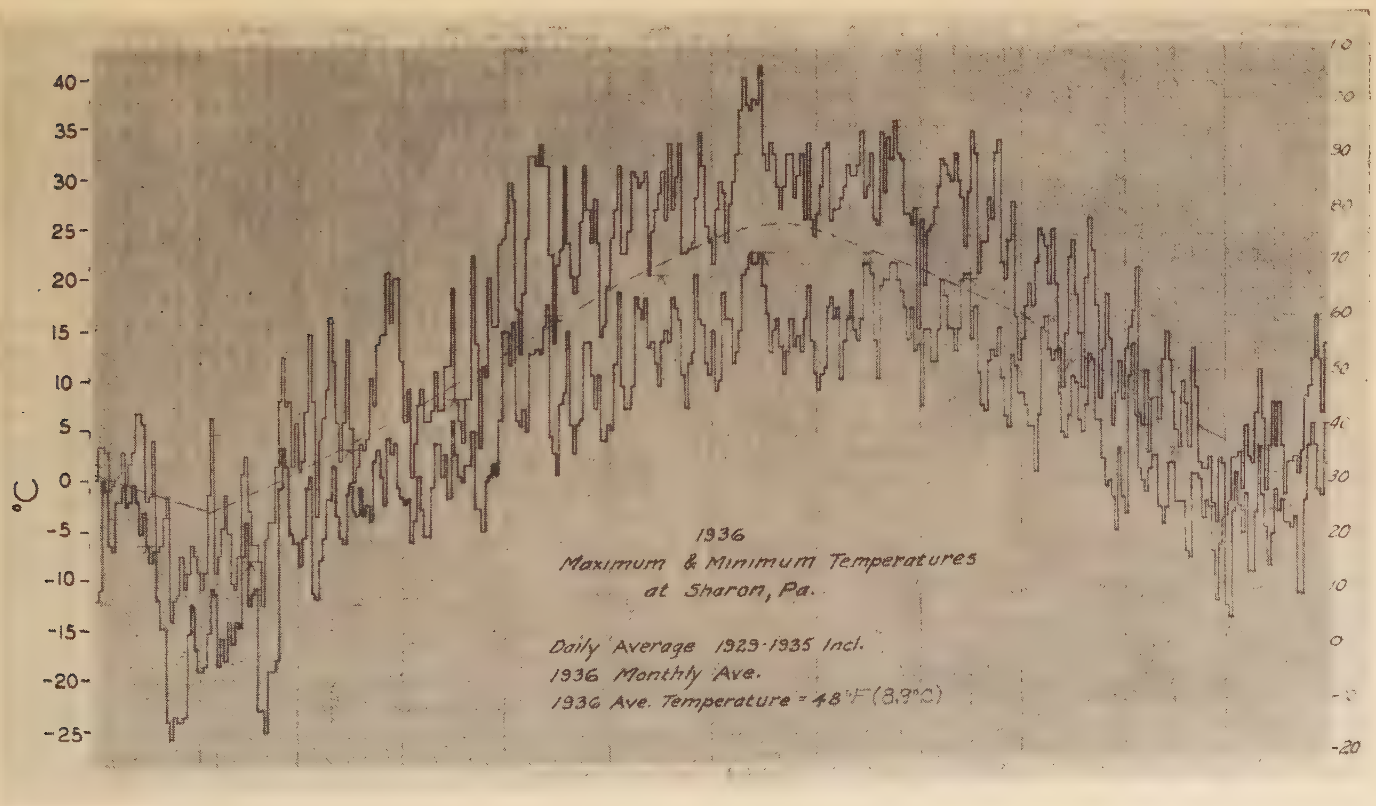

Figure 3. The daily temperature variations at Sharon, 1936

Table II. Reference Values and Testing Temperatures, in the Room-Temperature Range, Specified in October 1939 ASTM Standards on Electrical Insulating Materials

Material	Test or Treatment	Temperature or Temperature Range (Deg C)	Relative Humidity (Per Cent)
Sheet and plate	Physical	25 ±8	
	Conditioning	25	40
Laminated tubes	Physical	25 ±8	
Laminated rods	Physical	25 ±8	
Varnished cloth	Elongation	20 to 30	
Varnishes	Density	25 ±1	
	Viscosity	25 ±0.2	
	Time of drying	25	
	Conditioning	25 water	
Varnished cloth	Conditioning	20 to 30	60 to 65
	Power factor	25 to 30	
Flexible varnished tubing	Conditioning	20 to 30	50 to 55
	Aging	20 approx.	
Shellac	Iodine number	21.5 to 22.5	
Shellac varnish	General	21 to 32	
	Iodine number and drying time	20 to 30	
	Special	20	65
	Specific gravity	20	
Molded materials	Tensile strength	20	
	Dielectric	25	
	Water absorption	25 ±2	
Phenolic laminated sheet	Power factor	20 to 30	
Laminated tubes	Water absorption	25 ±2	
Laminated round rods	Water absorption	25 ±2	
Sheet and plate	Tensile strength	20	
	Rate of absorption	25 ±2	
	Total absorption	20 to 30	
	Bonding strength	20 approx.	
	Hardness	25 ±2	
Insulating oils	Dielectric	20 to 30	
Electrical porcelain	Tensile strength	20 approx.	
Filling and treating compounds	Power factor	20 to 25	
Untreated paper	Conditioning	20 to 30	65
Friction tape	Adhesion	20 to 22.2	less than 80
Rubber tape	Physical	20 to 28	
Rubber gloves	Electrical	15 to 32	
Asbestos yarns	Conditioning	21	65

above the floor and for a suspension-insulator string, the temperature measurement might be made as high as 30 feet above the floor. The average temperatures experienced indoors at Sharon are shown in figure 1*B*. These temperatures were recorded at one of the test floors where apparatus is subjected to the usual standard commercial tests as well as to other tests that may be required. The form of this average curve is practically similar to that of figure 1*C*.

(*c*). *Typical of Living Quarters Such as Homes, Offices, and Laboratories in Smaller Rooms.* In a well-heated building, consisting of smaller quarters, during the winter months, the temperature is 24±1 degrees centigrade. This conclusion has been reached from the temperature measurements over a period of time in the engineering laboratory building at East Pittsburgh.

From the foregoing, therefore, the problem of reference temperature and correction factors is twofold. In the first place, the desirability of keeping corrections small should be kept in mind chiefly because of inaccuracies and variations in the original correction-factor data. The undesirable effect of discrepancies due to very large correction factors can be somewhat minimized by using reference values representing average conditions. Thus, for outdoor testing as in case (*a*), in correcting data to a standard temperature of 25 degrees centigrade the corrections are, in most cases, larger than if a lower temperature were used as a reference value. The 25-degree-centigrade reference value has merit for case (*c*) and also for case (*b*), though it is apparent that there is not much to choose between 25 degrees centigrade and 20 degrees centigrade in these two cases. However, as a general rule, it is desirable to have the reference temperature higher rather than lower than the average, for it is easier to heat than to refrigerate to obtain standard conditions for testing. The second part of the problem pertains to dependable correction factors which are desirable in view of the inherent variations in atmospheric conditions.

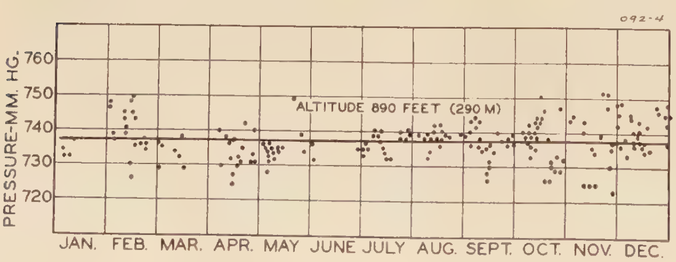

Figure 4. The barometric pressures for tests at Sharon, 1936–38

Barometric Pressure (Altitude)

The barometric pressure of 29.92 inches (760 millimeters) of mercury has been adopted universally as a standard reference value. This represents average conditions at sea level. The pressure of the atmosphere affects the thermal limits and the voltage rating of apparatus. Much apparatus is tested and used at elevations above sea level and consequently these effects cannot be ignored.

For a given location, however, the variations encountered in barometric pressure throughout the year are relatively small. Figure 4 shows readings at the Sharon laboratory during 1936–38. Each reading was taken at the time of a voltage flashover test. A ±1.5 per-cent band from the average includes practically all variations and a detailed examination of the records shows that diurnal variations seldom exceed 0.5 per cent. In a few instances only did the barometer vary from one day to the next as much as 2 per cent. To the meteorologist, these variations are an important measure of the trend in the weather or of prevailing conditions, but for the engineering purpose of this survey, the data hardly permit other than an average curve drawn through 735 millimeters mercury. This average value of mercury column corresponds quite well with the altitude of the Sharon laboratory which is 890 feet (290 meters). The effect of altitude on barometric pressure[7] is shown in figure 5.

The AIEE TRANSACTIONS for 1913 indicate that the standards in use at the time prescribed a correction of one per cent of the observed rise in the temperature of apparatus for each 10-millimeter deviation from the standard pressure of 760 millimeters. The present standards state that specified ratings hold for elevations up to 1,000 meters. This is a gratifying example of the simplification of practice in using a reference value, which is so desirable. It is noted in passing that AIEE Standard No. 11 for Railway Motors states: "Machines rated in accordance with these standards may be tested at any altitude not exceeding 1,200 meters and no correction shall be applied to the observed temperature rise". AIEE Standard No. 16 for Railway Control Apparatus gives the usual figure of

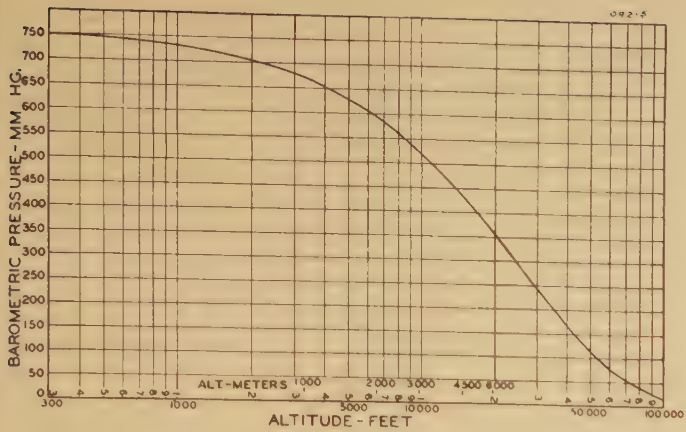

Figure 5. The effect of altitude on barometric pressure

1,000 meters. AIEE Standards for Transformers in addition to the 1,000-meter range give a correction for temperature rise tests made at altitudes greater than 1,000 meters.

At 1,000 meters the normal barometric pressure is 675 millimeters. Based on the old AIEE rule, an observed temperature rise at this altitude would be reduced eight per cent by the correction. As indicated above, present practice is to ignore altitude corrections up to 1,000 meters and to classify equipment for use at higher altitudes as "high-altitude apparatus". This applies to voltage as well as to thermal ratings. This simplification of the problem recognizes the impropriety of permitting a few applications to complicate the majority of ratings and measurements. For voltage flashover measurements, however, it is standard practice to combine barometric and temperature corrections under relative air density.

A recent occurrence is a backward step in progress toward uniformity of engineering practice. The United States Weather Bureau in July 1, 1939, adopted the practice of using the millibar as the unit of pressure. A bar is one dyne per square centimeter and 1,013.3 millibars corresponds to 760 millimeters, the standard atmospheric pressure. Several years ago the millibar was adopted for aerological observations and enjoys international use in this limited field. From an engineering point of view this action is regrettable. Barometric pressure invariably is expressed in terms of the height of a mercury column, both in standards and in laboratory practices. The use of Weather Bureau data will therefore require the use of a conversion factor.

The problem of barometric pressure in engineering measurements is a case where a single standard exists and where agreement on the unit of expression is reasonably consistent. Corrections have been minimized by standardizing on a range where possible. This fortunate situation is partly because the range of pressure variations in practice is small and the effects thereof on measurements and ratings correspondingly small. The growing use of electrical apparatus for aeroplanes eventually may lead to some modifications of present practices concerning ratings.

Humidity

Nearly 30 years ago the effects of humidity of the air on temperature rises of machinery were investigated and found to be negligible. It was also found that sphere-gap spark-over values were not influenced by humidity. Changes in

Table III. Reference Values in Apparatus Standards

		Reference Values**			
Standard*	Apparatus	Temperature (Deg C)	Barometric Pressure (Mm)	Humidity (Mm Hg)	Correction Factors Specified
AIEE No. 4—1940	Measurement of test voltage in dielectric test	25	760	15.45	Relative air density
AIEE No. 41—1940	Insulator tests (insulators)	25	760	15.45	
AIEE—Bushings	ELECTRICAL ENGINEERING, December 1934; AIEE Paper 40-37†	25	760	15.45	Relative air density, humidity, water resistance
ASA—1940—Proposed	Transformers, regulators, and reactors	25	760	15.45	Temperature rise above 1,000 meters
ASA—*C*50—1936	Rotating electrical machinery	25	760		Temperature cooling air and windage losses at high altitude
AIEE No. 19—1938	Oil circuit breakers	25	760	15.45	Voltage rating and temp. rise at high altitudes. Water resistivity
AIEE No. 22—1925	Disconnecting and horn-gap switches	Reference values and correction factors for numbers 22, 20, 28, and 26 substantially as in number 19			
AIEE No. 20—1930	Air circuit breakers				
AIEE No. 28—1936	Lightning arresters				
AIEE No. 26—1936	Automatic stations				
AIEE No. 18—1935	Capacitors	Leakage tests at 20 deg C			
AIEE Paper 40-38‡	"Recommendations for High-Voltage Testing"	25	760	15.45	Humidity corrections for rod gaps, insulators and bushings, relative air density
AIEE standards on conductors	Aluminum, copper, etc.	Resistance, temperature coefficient, and density of metal specified at 20 deg C			
IEC standards	High-voltage practice, insulators, and conductors	20	760	11	

* Some of the AIEE are also ASA standards.

** Apparatus standards almost invariably specify an altitude not exceeding 1,000 meters as usual service condition. AIEE Standard No. 11 ("Railway Motors and Other Electrical Machinery on Rail Cars and Locomotives") is the exception as it gives 1,200 meters.

† AIEE TRANSACTIONS, volume 59, 1940 (October section), pages 590–1.

‡ Committee report, AIEE TRANSACTIONS, volume 59, 1940 (October section), pages 598–602; also ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), June 1937.

Table IV. Average Temperatures*

Climatic Summary of United States—Weather Bureau, United States Department of Agriculture (Degrees Centigrade)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Average
1.	Boston, Mass.	−2.1	−2.0	2.4	8.0	14.1	19.2	22.2	21.0	17.6	12.0	5.8	0.1	9.8
2.	New York, N. Y.	−0.6	−0.6	3.6	9.3	15.5	20.4	23.3	22.4	19.2	13.3	6.8	1.2	11.2
3.	Philadelphia, Pa.	0.5	0.9	5.2	11.1	17.1	22.0	24.7	23.6	20.2	14.1	7.6	2.2	12.5
4.	Baltimore, Md.	1.5	2.1	6.3	12.2	17.8	22.9	25.4	24.3	20.4	13.9	8.2	2.9	13.2
5.	Washington, D. C.	1.0	1.8	6.3	12.0	17.8	22.5	18.8	23.7	20.2	13.9	7.5	2.5	12.8
6.	Albany, N. Y.	−4.7	−4.6	0.8	8.0	14.8	19.9	22.6	21.4	17.5	10.9	4.3	−2.1	9.2
7.	Buffalo, N. Y.	−3.8	−4.3	−0.2	5.9	12.2	18.0	21.0	20.3	16.8	10.4	3.9	−1.6	8.3
8.	Pittsburgh, Pa.	−0.6	−0.2	4.4	10.5	16.7	21.3	23.6	22.4	19.2	12.7	6.0	1.0	11.5
9.	Columbus, Ohio	−1.6	−0.9	4.4	10.6	16.6	21.4	23.9	22.7	19.8	12.7	5.6	0.2	11.3
10.	Detroit, Mich.	−4.2	−3.3	1.0	7.8	14.3	19.6	22.4	21.3	17.6	11.2	3.9	−1.7	9.2
11.	Indianapolis, Ind.	−2.0	−0.7	4.7	11.3	17.1	22.1	24.4	23.2	19.5	13.0	5.6	0	11.6
12.	Chicago, Ill.	−4.5	−3.1	2.2	8.4	14.0	19.5	22.6	21.9	18.4	12.1	4.4	−1.7	9.6
13.	St. Louis, Mo.	−0.2	1.6	7.0	13.6	18.9	23.8	26.3	25.2	21.2	14.3	7.0	1.5	13.4
14.	Denver, Colo.	−1.0	0.3	4.0	8.5	13.6	19.2	22.2	21.6	20.8	10.6	4.4	−0.1	10.1
15.	Salt Lake City, Utah	−1.6	1.0	5.3	9.9	14.4	19.7	24.5	23.7	18.0	11.4	4.9	−0.2	11.0
16.	Atlanta, Ga.	6.1	7.5	11.5	16.1	20.7	24.5	25.7	25.2	22.8	17.0	11.0	7.0	16.3
17.	Little Rock, Ark.	5.4	7.1	11.9	17.0	21.1	25.4	27.2	26.7	23.6	17.6	11.2	6.7	16.8
18.	New Orleans, La.	12.6	14.0	17.3	20.6	24.1	27.2	28.0	28.0	26.4	21.7	16.7	13.1	20.8
19.	Houston, Texas	11.8	13.3	17.1	20.8	23.9	27.3	28.5	28.4	26.1	21.5	16.3	12.5	20.8
20.	Miami, Fla.	19.7	20.0	21.8	23.3	25.3	26.8	27.6	27.8	27.2	25.3	22.6	20.3	24.2
21.	Seattle, Wash.	4.3	5.5	7.2	9.8	12.7	15.3	17.7	17.6	14.9	11.3	7.8	5.4	10.8
22.	Portland, Ore.	3.9	5.7	8.4	11.1	14.1	16.8	19.5	19.4	16.5	12.5	7.9	5.1	11.8
23.	San Francisco, Calif.	9.9	11.5	12.2	13.1	13.8	14.8	14.8	15.1	16.3	15.8	13.7	10.7	13.5
24.	Los Angeles, Calif.	12.8	13.3	14.2	15.5	16.8	19.2	21.3	21.8	20.8	18.5	16.6	13.8	17.2

* Average for the various locations in from 40 to 100 years.

flashover values of insulators and point gaps with humidity were observed, but it was less than 10 years ago that more complete quantitative tests[8] were started. AIEE Standards No. 41 for insulators gave a formula for determining the humidity from the wet- and dry-bulb temperature readings in terms of the vapor pressure in inches of mercury and specified 0.6085 inch as the standard humidity. It was stated that flashover voltage shall be determined at or corrected to this standard humidity, but no correction factors were given and the control of humidity for much high-voltage testing was impractical. The standard humidity value was arrived at by choosing 65 per cent relative humidity at 25 degrees centigrade and 760 millimeters pressure as the standard. This represents average conditions in the summer months when many insulation troubles appear due to lowered leakage resistances and to the lightning season.

The annual humidity variations at the Sharon and Trafford laboratories as measured in the course of high-voltage testing are shown in figures 6 and 7 and may be regarded as typical of the more populated sections of the country. Diurnal variations in the absolute humidity of 0.10 inch mercury are common, but seldom exceed 0.20. From one day to the next, the humidity may vary from 0.20 to 0.30 inch mercury. The total spread for the year may reach 0.80 inch mercury, to which amount there corresponds a humidity correction factor of 25 per cent for some of the station and line apparatus. The annual average for the recorded data in the figures is close to 0.40 inch mercury. In the summer months, the average is above 0.60 inch mercury. It is at once seen that from a laboratory viewpoint the 0.6085 inch standard is too high. About 80 per cent of the testing is carried on at substandard conditions. This means a higher percentage correction factor and test results are correspondingly more at the mercy of the accuracy of the correction factors. These, of course, were based on a limited amount of data. However, the difficulties of changing the standard on which so much work has been based in determining insulation values and in setting insulation levels have made acceptance of the above undesirable feature much more attractive than the confusion of changing.

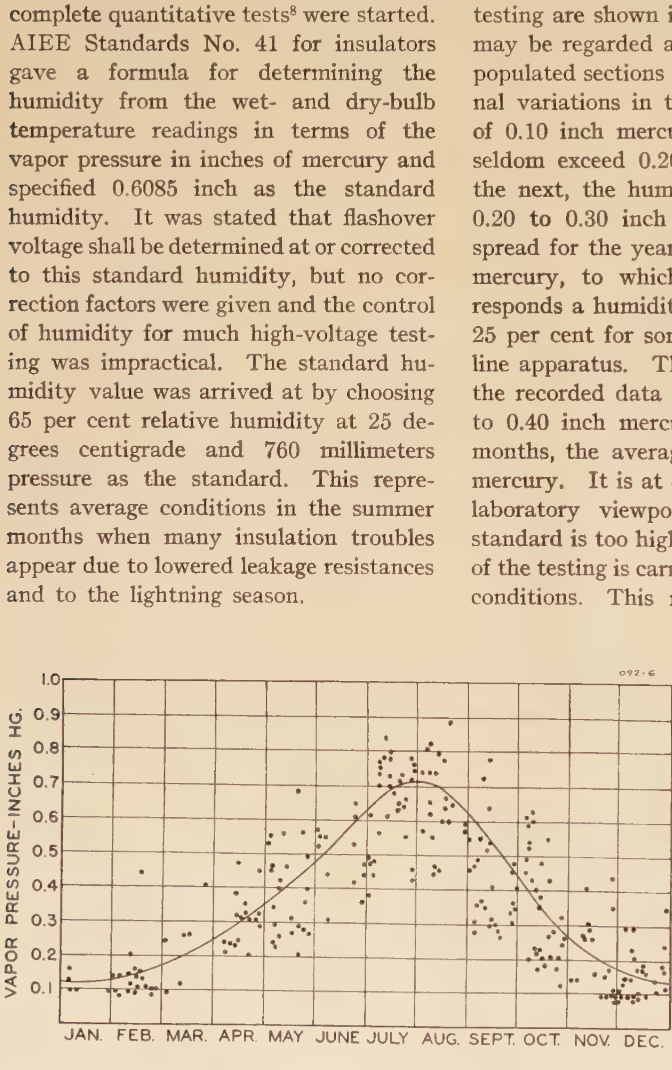

Figure 6. Humidity conditions at the Sharon high-voltage laboratory for outdoor tests, 1936–38

The laboratory subcommittee[9,10] of the EEI–NEMA Joint Committee on Coordination of Insulation have been working on the problem of the influence of humidity in connection with insulation problems for many years. Similarly, the International Electrotechnical Commission has carried on work of this nature abroad. The IEC has adopted a standard humidity of 11 grams per cubic meter, which corresponds to 0.45 inch vapor pressure. This is much closer to average testing conditions throughout the year. It would be convenient to have the United States and International standard agree to facilitate comparing data. This is a matter for the interested committees to consider. Fundamentally, the problem is one of the inconvenience of changing established values rather than of the intrinsic merits of a particular standard.

An undesirable situation prevails in connection with wet flashover testing. AIEE standards for circuit breakers and for transformers call for wet testing of bushings with a precipitation of 0.1 inch

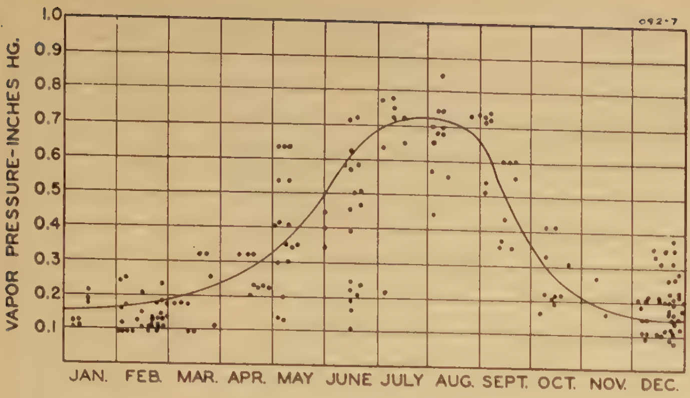

Figure 7. Humidity at the Trafford laboratory for indoor tests, 1934–38

per minute and a resistivity of 12,000 ohms per centimeter cube. AIEE standards for insulators specify wet flashover testing at a precipitation of 0.2 inch per minute and a water resistivity of 7,000 ohms per inch cube. AIEE standards for lightning arresters specify at least 0.1 inch of water per minute with the resistivity of 5,000 ohms per inch cube. The IEC groups have discussed standardizing on 3 millimeters per minute precipitation and 9,000–10,000 ohms per centimeter cube resistivity. A committee has been appointed to study and report on this situation and it is hoped that a simplification of testing procedures will result.

Summary

Reference values in present use are partly a product of history and were partly selected as a result of analysis. In some cases they represent average conditions and sometimes they do not. For certain applications different standardizing groups use different values and co-operative activities are thereby hindered.

An attempt has been made here to show the relation of reference values to variations found in practice. In most cases correction factors are available to correct measured values to standard conditions. The importance of correction factors is shown by figure 8 which gives the correction factor for humidity for the 60-cycle flashover voltage of suspension insulators. This indicates a correction of 16.5 per cent for tests made at 0.1 inch vapor pressure, a common condition in the winter months. Hence, from this point of view the selection of reference levels to minimize correction factors is to be recommended.

Attention is called to existing conditions, particularly where they are not conducive to easy comparisons of testing data and to simple testing procedures. It is hoped to stimulate the study of the problems involved and to assist present and future standardizing bodies in avoiding the confusion of the past and in organizing further work on a rational basis. At best all reference values and specified testing ranges must be a compromise for broader variations encountered by equipment under service conditions. Therefore, it seems reasonable to minimize the number and the ranges of the reference conditions.

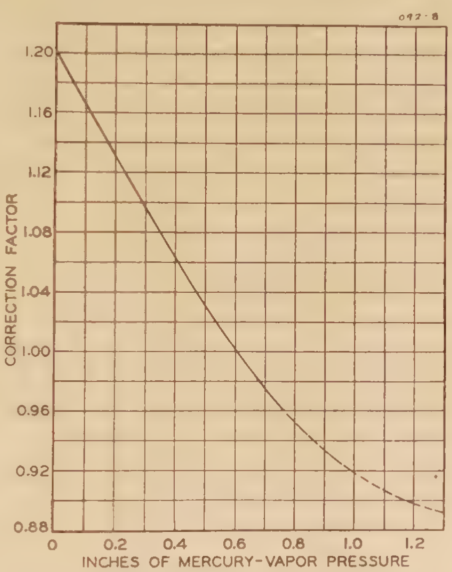

Figure 8. The importance of correction factors is indicated by the 20-per-cent spread in flashover voltages for the changes in absolute humidity indicated in figures 6 and 7

Humidity correction factors for 60-cycle flashover of rod gaps and suspension insulators; multiply measured kilovolts at humidity of abscissa by the correction factor

Standard humidity 0.6085 inch (15.45 millimeters)

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Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 Supplement to Electrical Engineering—Transactions Section.

Rating of Potential Devices and Suggested Material for a Standard

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THERE has been an evident need for an exposition of the factors relating to the rating of capacitance potential devices and to their application. It is our intention to review this situation indicating the several limitations which govern ratings and application, and to offer material which may be used in the preparation of standards for potential devices. Vacuum-tube equipment is not covered. The authors were requested by the AIEE relay subcommittee to write a paper outlining the basis of rating for the purpose of formulating standards.

Description of Device Circuits

The potential device may be defined as a voltage-transforming equipment used in conjunction with a high-voltage bushing or capacitor as a source of energy to provide a low voltage suitable for operating instruments and relays. The output voltage may be corrected by one of several means to obtain the desired instrument voltage and phase angle.

Lines of Devices

Practice has resulted in two varieties of capacitance devices, one for operation with bushings having a capacitance tap, and one for operation with coupling capacitors such as used for carrier-current work. The former is commonly referred to as a "bushing-potential device" and the latter as a "coupling-capacitor potential device".

Types of Devices

Practice has also resulted in two general types of devices as used with coupling capacitors, and they may be designated as "quadrature" and "in-phase", respectively. With the "quadrature device" the maximum output is obtained when the phase angle between the output voltage and the impressed line-to-ground voltage of the phase to which the device is connected through the coupling capacitor is approximately 90 degrees. With the "in-phase device" the rated output is obtained with these voltages substantially in phase. It is not essential, however, that the quadrature device always be adjusted for 90 degrees, and hence it may be more aptly termed "out-of-phase" device. It is essential that the in-phase device always be adjusted for the in-phase relation, to obtain rated output and performance. However in some cases, an in-phase device may be adjusted to obtain an angular shift at the expense of rating and performance characteristics.

Device Circuits

Much has been written about the theory of operation of these devices. Basically, the device consists of a transformer for voltage reduction and a reactance, or auxiliary burden, for phase-angle control. When used with a coupling capacitor the device may be connected in series with the main capacitor, or in shunt with a portion of it, whereas when connected to an apparatus bushing, the shunt arrangement only is used.

The most usual circuit arrangements are as shown in figure 1, (*a*)—(*f*).

Quadrature or Out-of-Phase Circuits. The circuit of figure 1*a* is the simplest and least useful and may be used when the phase angle of the secondary voltage is a matter of indifference and the load burden is exactly right to obtain the required voltage. If the load burden becomes disconnected the voltage rise will be limited only by the insulation strength of the transformer, or by the flashover of a protective gap. Its use should be discouraged.

Figures 1*b* and 1*c* are the circuits commonly used with the out-of-phase devices, and it should be noted that in figure 1*c* the auxiliary burden must include an inductive reactance to compensate for the capacitive reactance of C_2, if true quadrature performance is desired. The magnitude and phase angle of the output voltage is controlled by adjusting the value of the auxiliary burden, which consists of resistance, inductance, and capacitance. If the load burden becomes disconnected the voltage will assume a value determined by the setting of the auxiliary burden.

In-Phase Circuits. The circuits of figures 1*d*, 1*e*, and 1*f*, are those commonly used with the in-phase devices, depending upon the location of the control, or series, reactance Z_x. The value of the series reactance is closely equal to the reactance of the auxiliary, or shunt, capacitor C_2 and is adjustable, mainly for phase-angle control. The capacitor C_a is also adjustable in value to correct the power factor of the burden to unity. If the device secondary becomes short-circuited the voltage on the device primary will rise and be limited only by the losses or by the flashover of the protective gap.

Procurement of voltage at zero phase angle error primarily involves the use of a tapped bushing, tapped capacitor, or the equivalent, which in reality becomes a capacitance potentiometer. The tap voltage when supplying a totally capacitive burden will be in phase with the line-to-ground voltage of the coupling capacitor or bushing. A burden, other than zero power factor, will cause a phase displacement of the output voltage depending on its location in the circuit and the angular relation of the capacitor charging current and the burden current. This inherent phase displacement is corrected by the use of the inductive reactance Z_x.

Factors Affecting Rating

The rating of a potential device will depend upon economic and performance limitations that may be imposed. Factors involved in determining rating are:

1. Line voltage and frequency
2. Capacitance (electrostatic capacity) of the bushing or coupling capacitor
3. Permissible operating tap voltage on primary of device transformer
4. Insulation level of the device, and shunt or auxiliary capacitor
5. Characteristics and requirements of burden to be energized
6. Over-all performance requirements

Available Volt-Amperes

The maximum volt-amperes available for potential-device operation depends on the line-to-ground charging current through the bushing or coupling capacitor and the operating tap voltage at which the potential device diverts this current for instrument use. Roughly the prod-

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1. For all numbered references, see list at end of paper.

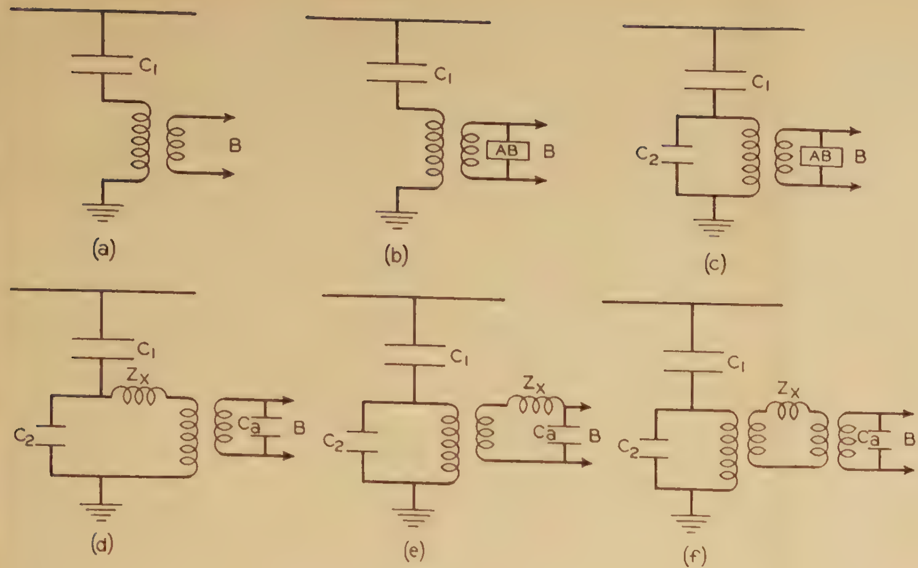

Figure 1. Typical circuits used for potential devices

C_1—Line-to-tap capacitance, sometimes coupling capacitance

C_2—Tap-to-ground capacitance, sometimes auxiliary capacitance, sometimes shunt capacitance

B—Useful burden

AB—Auxiliary burden for control

C_a—Power-factor-correction capacitance

Z_x—Series reactance for control

uct of these two quantities represents the maximum volt-amperes available from the transmission line. Practical considerations place a limit on the charging current and operating tap voltage. The voltage rating of the bushing, or the actual carrier coupling, fixes the capacitance. The operating line voltage and frequency determine the charging current that passes through this capacitance.

Watts Output

The output in watts of a potential device may be more accurately expressed:[1]

$$W = 2\pi f C_1 E E_2 \sin \alpha - K$$

where f is the system frequency, C_1 is the capacitance line to tap, E and E_2 are respectively the line and tap voltage to ground with the angle α between them. K represents the loss in the device network. The actual rating of a device is somewhat less than the maximum theoretically available to insure satisfactory operating performance. The term $2\pi f C_1 E$ is the charging current and term E_2 is the operating voltage at which the potential network is normally energized. This voltage usually dictates the insulation level of the transformer and the shunt or auxiliary capacitor which will be used in the circuit.

Effect of Series Reactance

The use of series reactance for phase-angle control (in-phase device) will affect the transformer operating voltage and the resultant voltage on the auxiliary, or shunt, capacitor. The circuit may be analyzed by several methods. However, without going into detail, the network resolves itself into an essentially parallel resonant circuit wherein the bushing or coupling capacitor capacitive reactances are fixed and the equivalent inductive reactance may be varied. The operating tap voltage will increase as the inductance in the circuit is increased, up to the point of resonance, for any fixed load impedance. The rating of a device must not be such that will result in a voltage across the tap and transformer in excess of their individual insulation ratings.

Protective Gap

A protective gap is connected across the tap circuit or transformer primary to provide overvoltage protection in service, and when so protected the device should be able to withstand the overvoltages to which the coupling capacitor or bushing may be subjected. The setting of this gap must be co-ordinated with the normal-frequency voltage that may be obtained during the fault period and with the voltage rating of the component parts of the circuit to be protected. The gap should not operate at less than twice normal voltage at normal frequency, otherwise incorrect voltage may be imposed on the relays. Thus the setting of an insulation level for the component parts of the device will depend on the maximum normal operating voltage of the tap circuit or potential transformer, which in turn will govern the output of the over-all equipment for a given voltage class of bushing or coupling capacitor. Naturally economic factors will also affect the setting of the insulation level and ultimate size of the equipment.

Burden Requirements

The requirements of the burden to be energized, such as phase angle displacement of the voltage and permissible ratio error will affect the required characteristics and rating of the device. For instance, if voltage indication only is required at normal operating voltages, device regulation and phase-angle displacement are of no concern and the simplest form of device would be satisfactory. On the other hand, if certain types of high-speed relays are to be energized a much more accurate device will be required. This latter type of burden requires an accurate reproduction of the primary voltage both as to phase angle and ratio over a large range of line voltage and secondary burden. Nonlinear burdens represent a special case and their use leads to instability of the combined device and burden circuit for certain conditions of operation.

Performance Features

The over-all performance of a device includes:

(*a*). *Performance Characteristics*

1. Regulation, or change in ratio and phase angle, with variation in burden, at constant applied voltage.

2. Regulation with variation in applied voltage, at constant burden impedance.

Note: The regulation is usually given on the basis that the device is initially adjusted for normal voltage and burden impedance.

(*b*). *Transient Characteristics*

The transient characteristics consist of the rapidity and fidelity with which the device follows changes in the system voltage, and the freedom from instability under normal and fault conditions.

Regulation

The ratio and phase-angle performance of a device may be represented by:[2]

$$E_b = E_{bo} - I_b Z \qquad E_{bo} = \frac{A}{n} E_h$$

where E_b and I_b are the burden voltage and current respectively; E_{bo} the no-load voltage; Z the total equivalent potential device impedance; E_h the line-to-ground voltage, A the relation between certain impedances, and n the ratio of the potential-device transformer. These relations show that increased burdens on a given device generally result in in-

creased ratio and phase-angle errors. This is due to the increased range of voltage on the potential device or tap circuit and to increased losses in the potential network.

Transients

Transient performance depends on the constants of the potential network used, the power factor, and type of the burden energized. All of these are interrelated with the device rating and the excitation requirements of the potential network.

Effect of Temperature Changes

The effect of temperature changes on the performance of potential devices may be considered in two steps: the effect inherent in the device itself; and the effect resulting from the changes in burden characteristics due to temperature changes. In the case of the in-phase device the temperature effect is practically negligible from either consideration for the usual conditions of operation. For the case of the out-of-phase device the inherent effect is also negligible except in regard to the coupling capacitance (auxiliary or shunt capacitance not used) for which a change of $2^1/_2$ per cent may take place for a temperature change from -20 degrees to 130 degrees Fahrenheit. Changes in burden, including the auxiliary burden, due to changes in temperature affect the performance in accordance with the characteristic curve.

Basis of Rating

Potential-device rating is expressed on definite primary and secondary voltages, the watts output, and the performance characteristics. The primary voltage ratings are the standard high voltages such as 115 kv, 138 kv, etc. The corresponding secondary voltages are 115 and/or 66.4.

The output rating of potential devices is given in watts, instead of volt-amperes as is customary for potential transformers. This is done because the watts output is actually the limiting factor and also the best performance characteristics are obtained when the burden is substantially at unity power factor. The performance characteristics consist in limits of change in ratio and phase angle for variations in burden or primary voltage.

Operation at other than rated high voltage will affect the rated output watts, or secondary voltage, or both. For instance, a device may be applied on a 138-kv circuit at a point where the operating voltage is 132 kv. In this case rated watts output may be obtained but the secondary voltage normally will be 110 volts, etc.

Another case is where the apparatus is operated at a circuit voltage corresponding to the next voltage class below normal insulation rating. For such a condition a special device must be used and the device output is derated in proportion to the reduction in primary voltage, and normal secondary voltages and performance characteristics obtained.

Table I. Maximum Ratio and Phase-Angle Deviation With Variation in Applied Voltage

Per Cent Primary Voltage	Class A Ratio (Per Cent)	Class A Angle (Deg)	Class B Ratio (Per Cent)	Class B Angle (Deg)	Class C Ratio (Per Cent)	Class C Angle (Deg)
110	±1	±1	± 2	± 2	±2	± 5
100*	±1	±1	± 2	± 2	±2	± 5
85					±5	±10
25	±3	±3	± 6	± 6		
5	±5	±5	±12	±12		

* Device to be initially adjusted within these limits.

Effect of Bushing Capacitance

The low capacitance of apparatus bushings limits the charging current available for potential-device operation. Impulse characteristics of these bushings, and the apparatus in which they are installed, place a definite limit on the operating tap voltage and thus the capacitance of the tap for potential device operation. The higher-voltage bushings will have a larger charging current than the lower-voltage bushings and thus the bushing potential device ratings will vary with the voltage class of the apparatus bushing. These output ratings will vary for each of the accepted standards of primary voltage.

Effect of Coupling Capacitance

Coupling-capacitor potential devices will have the same rating for any voltage class and in general it is higher than for bushing potential devices. The capacitance of coupling capacitors for the various voltage classes will in general vary inversely with the voltage rating thus tending to maintain the same charging current and watt output regardless of the normal circuit voltage rating.

Grounded or Isolated Neutral

Potential devices may be used on either grounded-neutral, isolated-neutral, or impedance-grounded neutral systems. In the case of isolated-neutral systems, and sometimes for impedance-grounded systems, overvoltages in excess of the protective gap setting may occur on the unfaulted phases. Consequently the application of potential devices should be given special consideration under these conditions.

Choice of a Potential Device for Relaying

The in-phase device should be used where the following forms of relaying are involved: ground directional, phase directional, carrier pilot, pilot wire, distance.

The out-of-phase device may be used for any one of the following forms of relaying: ground directional, balanced current with voltage restraint, undervoltage or overvoltage. It should be noted that most directional ground relays are arranged for operation from in-phase devices. If an out-of-phase device is used, a change in the voltage circuit of the relay is generally necessary.

Ratio and Phase-Angle Characteristics

The potential device should be chosen having ratio and phase-angle accuracy commensurate with the degree of accuracy required of the relaying. Generally, the accuracy of any in-phase device is suitable for all except possibly some forms of distance relaying.

In the case of distance relaying using reactance-type elements, errors in current and voltage sources introduce the following error in distance measurement:

$$\text{Per cent error} = 100\left[1 - \frac{K_c}{K_p}\,\frac{\sin(\phi+\theta_p-\theta_c)}{\sin\phi}\right]$$

where

K_c = ratio correction factor of current transformer

K_p = ratio correction factor of potential device

ϕ = power factor angle of line

θ_p = phase-angle error of potential device (positive if leading)

Table II. Maximum Ratio and Phase-Angle Deviation With Variation in Burden

Per Cent Burden	Class A Ratio (Per Cent)	Class A Angle (Deg)	Class B Ratio (Per Cent)	Class B Angle (Deg)	Class C Ratio (Per Cent)	Class C Angle (Deg)
100*	± 1	±1	± 2	± 2	±2	±5
50	± 6	±4	±10	± 5	**	**
0	±12	±8	±20	±10	**	**

* Device to be initially adjusted within these limits.

** Limits cannot be set on account of the varying relationship between values of useful and auxiliary burdens.

θ_c = phase-angle error of current transformer (positive if leading)

If the per cent error is a positive quantity, the distance measured will be less than the actual distance.

If impedance elements, which are not sensitive to phase angle, are used the error, usually small, can be expressed as:

$$\text{Per cent error} = 100\left(1 - \frac{K_e}{K_p}\right)$$

Appendix

Suggested Material for a Standard for Potential Devices*

There is a need for co-ordinated practice in regard to potential devices and in this appendix there is presented material suitable for standards. It is hoped this will serve as the basis for the formulation of potential-device standards by the Institute.

These suggestions have been prepared by the authors, reviewed by the AIEE relay subcommittee, and are presented here for the purpose of bringing them to the attention of the industry for comment.*

Scope

These standards apply to potential devices for use with coupling capacitors and/or bushings.

Terminology

Potential Devices

The potential device may be defined as a voltage-transforming equipment used in conjunction with a high-voltage bushing or capacitor as an energy source, to provide a low voltage suitable for operating instruments and relays.

Note: The term "coupling-capacitor potential device" may be used to indicate use with coupling capacitors, and "bushing potential device" indicates use with bushings.

Ratio

The ratio of a potential device is the overall ratio of the line-to-ground voltage of the phase to which the device is connected to the secondary voltage of the device. (It is not the turn ratio of transformers used in the network.)

* Publication of this material with this paper authorized by the AIEE committee on protective devices at the Niagara Falls meeting, May 17, 1940.

Regulation

The term "regulation" designates the change in ratio and phase angle when the burden is varied over a specified range (burden regulation) with constant primary voltage; or when the line-to-ground voltage is varied over a specified range (voltage regulation) with constant burden impedance.

Standard Ratio

The standard ratio shall be such as to give standard rated secondary voltages at rated burden when coupling capacitors are used at their rated voltage.

Classification

Potential devices are divided into two types and three accuracy classifications.

In-phase type—zero phase-angle adjustment—two accuracy classes

Out-of-phase type—30 to 150 degrees phase-angle adjustment—one accuracy class

Types

In-Phase. The secondary voltage shall be adjustable to be closely in phase and have correct ratio with respect to the line-to-ground voltage of the phase to which the device is connected, and to remain so for all values of applied primary voltage and secondary burden within the rating of the device, subject to the allowable deviations as herein stated.

Out-of-Phase. The secondary voltage shall be adjustable to the desired phase angle and of correct ratio with respect to the line-to-ground voltage of the phase to which the device is connected, subject to the allowable deviation as herein stated.

Classes

The accuracy classifications are as follows:

Class *A*—High accuracy, in-phase type

Class *B*—Lower accuracy, in-phase type

Class *C*—Out-of-phase type—for use with coupling capacitors only

Rating

The rating of potential devices shall include

1. Circuit voltage
2. Line-to-neutral voltage
3. Maximum watts output
4. Secondary volts
5. Frequency

Performance Characteristics

The standard characteristics of potential devices shall be based on

(*a*). Rated line-to-ground voltage of the circuit

(*b*). A frequency of 60 cycles

(*c*). Standard secondary voltages

(*d*). Specified burden

For the in-phase devices the performance characteristics shall be based on a unity-power-factor burden.

Rated Watts Output and Standard Secondary Voltages

For coupling-capacitor potential devices the rated watts output and standard secondary voltages shall be:

Class	Main Winding Watts	Main Winding Secondary Volts	Auxiliary Winding Watts	Auxiliary Winding Secondary Volts
A	150	115/66.4	75	115
B	100	115/66.4	50	115
C	75	115		

For bushing potential devices the standard secondary voltages shall be as given in the following table. The rated watts output is dependent upon the standard bushing and is being studied further. It is hoped to reach a conclusion in time to incorporate the results in the adopted standards.

Rated Circuit Voltage (Maximum Kv)	Line-to-Neutral Voltage (Maximum Kv)	Secondary Voltage (Volts)
115	66.4	66.4 or 115
138	79.7	66.4 or 115
161	93.0	66.4 or 115
230	132.0	66.4 or 115
287.5	166.0	66.4 or 115

Performance Specifications

Variation in Applied Voltage

The regulation with constant burden impedance for variation in applied voltage shall not be greater than given in table I.

Variation in Burden

The regulation with constant primary voltage for variation in burden shall not be greater than given in table II.

Output at 50 and 25 Cycles

The output shall be reduced to 80 per cent for use on 50-cycle circuits. For use on 25-cycle circuits a special design is required.

Deviation of Circuit Voltage

Standard performance characteristics at proportionately reduced output ratings shall be maintained for a reduction in voltage from 5 per cent up to 20 per cent (that is, use of coupling capacitor of the next higher voltage class, in which case the watts output rating shall be reduced 20 per cent and a special design is required).

Power-Factor Correction

Coupling-capacitor potential devices shall be provided with a tapped capacitor in the

secondary circuit as follows: class A, 115 volt-amperes in 3.75-volt-ampere steps; class B, 75 volt-amperes in 5-volt-ampere steps.

In class C devices this feature is incorporated in the auxiliary burden.

Bushing potential devices shall be provided with tapped capacitor in the secondary circuit to correct the actual burden, assumed to be at 0.60 power factor lagging, to the rated burden at unity power factor, in 5-volt-ampere steps.

Adjustment Range and Steps

The maximum range over which adjustment shall be required and the maximum steps of adjustment shall be:

Class of Device	Maximum Range of Adjustment: Ratio (Per Cent)	Maximum Range of Adjustment: Phase Angle (Deg)	Maximum Tap Steps: Ratio (Per Cent)	Maximum Tap Steps: Phase Angle (Deg)
A	±5	±5	1	1
B	±5	±5	2	2
C	*	30–150	2	5

* Not specified.

Protective Gap and Grounding Switch

A protective gap set at not less than twice the maximum steady-state operating tap voltage shall be provided. A switch shall be provided for grounding the device primary.

Overvoltage Operation

Devices shall be capable of momentary operation with rated burden at circuit overvoltages not exceeding two times normal line-to-neutral voltage without becoming unstable.

Insulation Level

The insulation level of potential devices, and shunt and/or auxiliary capacitors, etc., in the primary circuit, shall be the same as used for instrument transformers of corresponding voltage class. The secondary winding, capacitors, etc., in the secondary circuit shall receive a test of not less than 2,500 volts, in accordance with instrument-transformer practice, proposed ASA Standards for Transformers, $C57$, page 34 table 7.

References

1. Application of Capacitance Potential Devices, J. E. Clem. AIEE Transactions, volume 58, 1939 (January section) pages 1–8.

2. Transient and Steady-State Performance of Potential Devices, E. L. Harder, P. O. Langguth, and C. A. Woods, Jr. AIEE Transactions, volume 59, 1940 (February section) pages 91–9.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 Supplement to Electrical Engineering—Transactions Section.

A Method for Detecting the Ionization Point on Electrical Apparatus

G. E. QUINN
MEMBER AIEE

When any part of the air path included in the insulating circuit of a piece of electrical equipment is overstressed, ionization occurs. The critical value of voltage is a function of the nature of the remainder of the dielectric circuit, the manner of use, surface conditions, the proximity of grounded conducting bodies, the temperature, and in some cases, the relative humidity. Ionization in air causes the formation of small quantities of ozone and oxides of nitrogen. The presence of ozone leads to accelerated aging of insulating materials, especially organic materials such as varnished cambric and paper. The oxides of nitrogen may combine with water to form nitrous and nitric acids which attack cellulose materials and metals. While increasing temperature tends to decrease the voltage at which ionization occurs or to increase its severity at a given voltage, this effect is somewhat offset by the fact that the acids formed are decomposed at temperatures above 80 degrees centigrade. cables have been known to fail in a few years when subjected to apparently mild ionization under high-humidity conditions. Ionization produces radio interference either by direct radiation or by conduction along the supply circuit or some paralleling circuit.

The minimum voltage at which ionization occurs on a piece of electrical equipment is of interest to both manufacturer and user. The necessity to arrest this condition and not wait until ionization is visible or audible has long been obvious with the result that a number of methods have been proposed for the determination of the voltage at which ionization occurs.[1–3] The method most commonly used at present is probably the one given in the "Report of the Joint Coordination Committee on Radio Interference of the EEI, NEMA, and RMA". Using this method the "radio noise influence voltage" of the equipment under test is measured and it is therefore essentially a radio-interference test. It is,

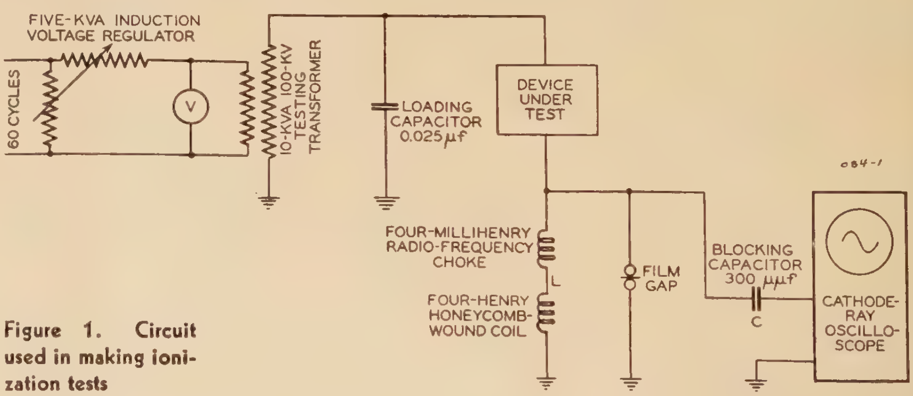

Figure 1. Circuit used in making ionization tests

Under certain conditions increased humidity on the other hand not only causes more severe ionization at a given voltage but increases the severity of the action on the cellulose insulation or metal parts which may be present. Nonleaded however, satisfactory as a means of detecting the voltage at which ionization occurs on apparatus which can be tested at locations not subject to stray interference. It is often necessary for this work to be conducted under severe stray field conditions and it is the purpose of this paper to describe a simpler and less expensive method which may be used under such circumstances.

In the proposed method a cathode-ray oscilloscope is used to detect the pulses, surges, or damped oscillations introduced into the charging current by ionization

Paper 40-84, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted September 30, 1939; made available for preprinting May 10, 1940.

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1. For all numbered references, see list at end of paper.

Figure 2. Test setup for determining ionization point on 5,000- to 5-ampere 15,000-volt current transformer

A circuit used with considerable success is shown in figure 1. A reactor L is inserted in the ground lead of the device under test and the voltage drop across this reactor is applied to the oscilloscope. Some time ago Lloyd and Starr[4] applied the drop across a resistor to an oscilloscope in a study of corona loss. While this method served its purpose it is not adequate for ionization-point determination. If this resistor is replaced by a suitable reactive shunt the usefulness of the method is greatly increased. Referring to figure 1 it will be noted that the reactive shunt is made up of a four-millihenry radio-frequency choke in series with a four-henry honeycomb-wound coil. This combination of impedance is used in order to obtain maximum deflection of the ionization components of current on the oscilloscope. The radio-frequency choke has a distributed capacitance of about one micromicrofarad and produces maximum drop for the high-frequency components of the ionization current while the four-henry coil is effective on the lower-frequency components. A blocking capacitor C is used in series with the oscilloscope in order practically to eliminate the test-frequency current appearing on the screen thus making it more readily possible to detect the first evidences of ionization. In addition, the oscilloscope may be operated with constant amplification as the voltage on the apparatus under test is increased.

A loading capacitor is connected in parallel with the device under test to provide a low-impedance path for ionization currents produced. By disconnecting this capacitor a simple means is provided for checking whether the oscilloscope is indicating ionization produced by the device under test or ionization inherent in the test setup. If the indication on the oscilloscope is due to ionization currents produced by the device under test, the indications will decrease. If it is due to a faulty test circuit the indications will increase because the short-circuiting effect of the capacitors will no longer be present.

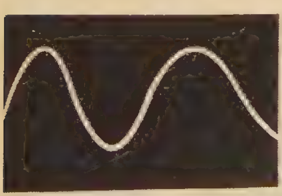
The oscilloscope is a standard model with self-contained amplifiers and the sensitivity is usually set for 0.005 inch per millivolt deflection of the beam. It has been found that further increase in sensitivity increases the magnitude of the indication only, without appreciably decreasing the voltage at which oscillatory discharges are first detected.

In setting up this equipment, care should be taken to have all high-voltage connections free from sharp corners and edges in order to prevent ionization from these sources. Ground connections should be solidly made and capable of carrying the full short-circuit current of the testing set. In addition, a film gap of low capacitance should be connected as shown in figure 1 for further protection of the operator. Figure 2 is a photograph of a typical test setup, and shows a 15,000-volt 5,000-ampere current transformer under test. A shielded lead is shown connecting the oscilloscope to the reactive shunt. The two coils which make up the reactive shunt L will be noted on the table in front of the current transformer.

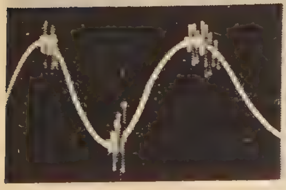
In using this setup the voltage applied to the device under test should be increased in about 200-volt increments and the oscilloscope observed at each value for indications of ionization. The sweep circuit of the oscilloscope should be adjusted for the test-circuit frequency or some submultiple thereof in order that the trace of the screen be stationary. The oscillatory discharges which accompany ionization appear superimposed on the charging current.

The definiteness with which the ionization point can be determined using this circuit can be seen in figure 3. The device under test in this case was a 3,000-volt lightning arrester. The marked difference between the oscilloscope traces obtained at 200-volt increments leaves no doubt as to the point of inception of ionization. These traces were obtained using a sensitivity of 0.005 inch per millivolt. Though the ionization point is not always as sharply defined in all pieces of equipment, it has been found that if the sensitivity is increased sufficiently oscilloscope traces similar to those shown on this figure may be obtained on any piece of equipment. The voltage at which ionization is detected at greatly increased sensitivity has been found to be not more than 200 volts below the value noted by a trained observer when the oscilloscope is set for normal sensitivity.

Figure 4 is an oscilloscope trace of ionization encountered at 6,000 volts on a 5,000-to-5-ampere 15,000-volt current transformer. The test circuit and sensitivity were the same as those used in obtaining the traces shown in figure 3.



5400 VOLTS



5600 VOLTS

Figure 3. Oscilloscope traces showing the point of inception of ionization in a lightning arrester

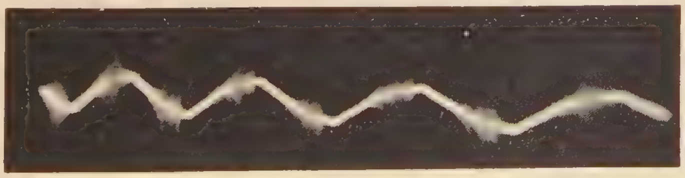


Figure 4. Oscilloscope trace showing ionization at 6,000 volts in a new 5,000- to 5-ampere 15,000-volt station-type current transformer

Table I. Results of Ionization Tests Using "Radio Noise Influence Voltage" Circuit and Cathode-Ray-Oscilloscope Method

Device Number	Type of Equipment	Minimum Voltage at Which Disturbance Was Noted: Increasing Voltage – Oscilloscope	Increasing Voltage – Noise Meter	Decreasing Voltage – Oscilloscope	Decreasing Voltage – Noise Meter
1	Lightning arrester (repaired)	600	600	550	550
		500	500	500	500
		500	500	500	500
	Avg.	550	550	500	500
2	Lightning arrester (repaired)	2,000	2,000	1,750	1,750
		1,750	1,750	1,750	2,000
		2,200	2,200	1,750	1,750
	Avg.	2,000	2,000	1,750	1,850
3	Lightning arrester (repaired)	500	500	Less than 500	2,500
		600	3,000	800	3,000
		1,000	3,000	600	2,600
	Avg.	700	2,200	Less than 700	2,700
4	Current transformer (repaired)	1,300	1,300	800	950
		1,500	1,500	1,700	1,700
		1,800	1,800	2,650	2,650
	Avg.	1,550	1,550	1,700	1,750
5	Current transformer (new)	9,500	9,500	6,100	6,100
		9,000	9,000	4,500	4,500
		9,000	9,000	5,000	4,500
	Avg.	9,200	9,200	5,200	5,050
6	Current transformer (new)	4,700	4,700	4,800	4,800
		5,300	5,300	5,100	5,100
		4,900	4,900	4,700	4,700
	Avg.	5,000	5,000	4,900	4,900

Visual corona on this transformer was not detected until the voltage had been increased to 16,500 volts. Although this transformer is of recent manufacture, it can be seen from the figure that there is unmistakable evidence of ionization at a voltage considerably below the intended operating voltage to ground. This may be taken as evidence of a defect in this transformer since transformers of identical design and similar manufacturing processes, which were tested at the same time, showed no evidence of ionization below operating voltage to ground.

A series of tests comparing the oscilloscope method and the "radio noise influence voltage" method were made recently under normal laboratory conditions. Throughout these tests, intermittent stray disturbances were picked up by the radio-noise meter. At times these became so severe that it was found necessary to delay the tests until the stray interference decreased sufficiently to permit a satisfactory determination of the amount of interference generated by the device under test. In the case of the cathode-ray oscilloscope the external disturbances were identified by the nature of their appearance on the screen and therefore did not materially interfere with the progress of the test. External disturbances appeared on the oscilloscope as random oscillations at no definite point, whereas the high-frequency discharges from the device under test were always repeated at definite points on the screen since the frequency of the sweep circuit was set at a submultiple of the test frequency.

The results of the tests given in table I are reported as the minimum voltage at which the frequency discharges and radio interference were detected for both ascending and descending voltage on each device tested. The results of the test show that with the exception of one measurement obtained on current transformer designated device number 5 the oscilloscope indicated high-frequency discharges at or below the minimum voltage at which interference was noted on the radio-noise meter.

It will be noted that on the lightning arrester designated device number 3 high-frequency discharges were observed on the cathode-ray oscilloscope at voltages considerably below those at which interference was noted by the radio-noise meter. In order to study this further arbitrary values of the amplitude of the discharges were obtained. These extended from 0.05 inch at 200 volts to 3.70 inches at 4,250 volts. The radio-noise meter first detected interference at approximately 3,000 volts. The insensitivity of the radio-noise meter at the low voltages may have been due to a lack of interference at the frequency to which it was tuned.

In all of these tests the radio set was tuned to a frequency of approximately 1,000 kilocycles. It was found on an additional test that the noise measured by the radio-noise meter increased appreciably as the tuning frequency of the receiver was increased from 1,000 to 1,400 kilocycles with constant voltage applied to the device under test. This is contradictory to claims made for this method and indicates that further work should be done along this line.

The cathode-ray-oscilloscope method of detecting the ionization point of equipment has been used on many other types of electrical equipment including sections of bus, ground and test switches, disconnect switches, cables, porcelain pin-type insulators, and distribution transformers. All this work has served to illustrate the importance of a standard method for determining the ionization point of equipment and the desirability of treating this as the basic problem rather than using the secondary approach of radio noise.

While it is admitted that further work needs to be done in connection with the determination of ionization voltages, it would appear that the following conclusions may be drawn:

1. A cathode-ray oscilloscope used in connection with an appropriate air-core reactor will detect high-frequency discharges at or below the minimum voltage at which radio interference may be noted by the "radio noise influence voltage" method.

2. Since ionization when continued over a long period of time might have a deteriorating effect on the apparatus under test, it is important to know the minimum voltage at which it occurs.

3. The oscilloscope method is simple and satisfactory and is not affected by stray fields.

4. The oscilloscope method is dependable as a means of detecting disturbances over a very wide band of frequencies.

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2. Bulletin No. 259 and 260, University of Illinois Experiment Station.

3. Measurement of Discharges of Dielectrics, A. N. Arman and A. T. Starr. The Institution of Electrical Engineers *Journal*, volume 79, July 1936, page 67.

4. Corona Loss Measurement by Means of the Cathode-Ray Oscilloscope, Lloyd and Starr. AIEE Transactions, 1927, page 997.

Discussion

Discussion will be found in the 1940 annual Transactions volume and in the 1940 Supplement to Electrical Engineering—Transactions Section.

Industrial Notes

Sales Appointments.—Harry L. Williamson, formerly assistant manager of cable sales for the General Electric Co., has been appointed manager of sales promotion for the Locke Insulator Corp., Baltimore, Md., a G-E affiliate. Mr. Williamson had been associated directly with General Electric since 1928. His affiliation with the cable section began in 1930 and he was made assistant manager of cable sales in 1936. . . . . The John A. Roebling's Sons Co., Trenton, N. J., has appointed Roger H. Clapp, formerly Philadelphia branch manager, as assistant general manager of sales. Mr. Clapp came to the Roebling company in 1936 and was manager of the Philadelphia branch until his present appointment.

Increased Westinghouse Production.—To meet transformer requirements under the Government's national defense program, production has been increased at the Westinghouse works, Sharon, Pa., world's largest plant devoted exclusively to transformer manufacture. Being built in the plant at present are 500 distribution and instrument transformers for Navy shipbuilding, also, three electric furnace transformers, among the largest ever built. One, rated at 12,000 kva, will supply current to an electric furnace in a steel mill which is turning out alloys for airplane parts. The last of seven 50-ton transformers for Bonneville Dam in Washington is nearing completion. These transformers are at 25,000 kva each.

Recent G-E Sales.—Included among recent General Electric orders is an 80,000-kw turbine-generator for the 465,000-kw Charles R. Huntley steam station of Buffalo Niagara Electric Corp., near Tonawanda, N. Y., as part of an expansion for this station which will involve a total expenditure of $6,000,000. Electric equipment for new hydroelectric power stations to be located at Nantahala and Glenville, N. C., consists of two G-E 27,000-kva, 150,000-volt, 3-phase transformers, and a 54,000-kva vertical waterwheel driven generator, together with a motor-generator exciter set for the Nantahala Power & Light Co. Four 9,000-kva, 150,000-volt, single-phase transformers are to be installed at the Glenville station.

Trade Literature

Recording Demand Meters.—Bulletin B-2234, 16 pp. Describes a complete line of recording kw-demand meters for all classes of services in common use. Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

Distribution Systems.—Bulletin 61, 16 pp. Describes feeder "busduct," "plugin busduct," and "plugin" devices and accessories used in industrial distribution systems. Prices are included. Frank Adam Electric Co., 3650 Windsor Place, St. Louis, Mo.

Oil Circuit Breakers.—Bulletin B-6003, 4 pp. Describes very large units available in standard ampere and interrupting capacity ratings from 15 kv to 69 kv. Bulletin B-6093, 4 pp., covers small units in standard ratings from 15 kv to 23 kv. Distinctive features include quick quench ruptors, high speed solenoid operator and accessible control cabinet. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Portable Substations.—Bulletin GEA-3413, 4 pp. Describes fully equipped, trailer mounted portable substations. They are applicable for emergency use, standby service for handling seasonal and other types of temporary overloads, to continue service during inspection or repair work, or to supply power for construction jobs and numerous other temporary power needs. General Electric Co., Schenectady, N. Y.

Wires and Cables.—Catalog 102, 36 pp. "Rubber Covered Wires and Cables—Service Entrance Cables". Describes and illustrates process of manufacture; covers standard rubber insulated building wires, service entrance cables; contains complete data with tables, etc., on small diameter (thin-wall) building wire, including methods of selecting wire sizes for new or rewiring installations. Examples of the manner of using these tables to determine proper conductor selection for various requirements are included. John A. Roebling's Sons Co., Trenton, N. J.

Power Plugs and Sockets.—Bulletin 500, 8 pp. Describes and illustrates a new series of power plugs and sockets designed for 5,000 volts and 25 amperes, and made in 2, 4, 6, 8, 10 and 12 contacts. All sizes are polarized so that it is impossible to make incorrect connections, even when using several sizes on a single installation. The cap is arranged so that a standard cable clamp can be used; connections are easily and quickly made, and cap body can be removed for inspection without disturbing wiring. Howard B. Jones, 2300 Wabansia Ave., Chicago, Ill.

Voltage Regulators.—Bulletin 51-2, 20 pp. Includes a comprehensive technical discussion, illustrated with 26 wiring diagrams showing how small, type TH Transtat voltage regulators may be used in multi-unit gangs and with auxiliary transformer equipment for controlling input voltage to loads which are outside the usual limits of kva, voltage, current or phase of the regulator element; also, complete descriptive data on type TH Transtat voltage regulators and type LC Transtat line voltage compensators. The text is accompanied by illustrations, outline drawings and a tabulation of standard ratings, with prices, weights and dimensions. Type TH Transtats are offered in larger sizes than were previously manufactured. These units are designed to provide an adjustable output voltage with regulation over a range of 0 to 113 per cent of input in small increments and without circuit interruption. Type LC Transtats are designed to permit manual correction of variations in line voltage, being a new design of regulator announced for the first time in this bulletin. American Transformer Co., 176 Emmet St., Newark, N. J.

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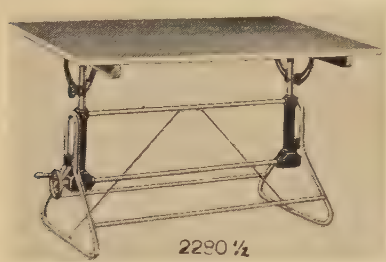
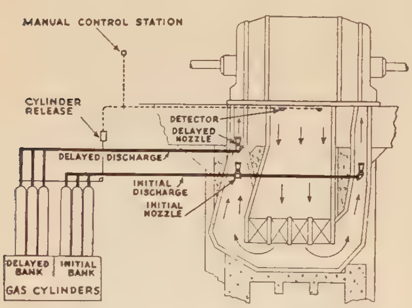
New Products

Drafting Tables.—Two new drafting tables developed by The Frederick Post Co., P. O. Box 803, Chicago, Ill., feature appearance as well as utility. They are constructed of satin chrome tubular steel, with table tops



of selected pine $1^1/_8$ inches thick. The type illustrated, "Primo Metapost", is quickly adjusted by turning a handwheel which will raise the working surface from 35 to 43 inches. The top of the table may be tilted from front to back at an angle of 60° by a manual adjustment of two hand clamps. Another model, the "Metapost" has the same adjustment features as the "Primo Metapost," except that instead of wheel control, two easily reached thumb screws permit the table top to be manually raised or lowered. These tables are available in 11 table top sizes ranging from 31 by 42 inches to 48 by 96 inches. Reference shelves, which can be furnished, and provide ample space for tracings, materials, etc., may be easily attached to either model.

Generator Fire Protection.—A new development in the protection of rotating electrical machines from fire, introduced by Walter Kidde & Co., 140 Cedar St., New York City, manufacturers of carbon dioxide extinguishing equipment, consists of the use of special shielded nozzles for the discharge of carbon dioxide into the ventilating



ducts of generators in event of fire. As shown in the illustration, the shielded nozzles are affixed to both the initial discharge and the delayed discharge pipes which carry the carbon dioxide from the storage cylinders to the ducts, and the refinement is said to eliminate objectionable high jet velocity and turbulence. Also, the new nozzles aid in achieving a more rapid and uniform distribution of the fire-killing gas throughout the machine.

Cable Terminal.—The "streamlined" cable terminal, type SNA-H, developed by the Burndy Engineering Co., Inc., 459 E. 133rd St., New York City, is especially designed to facilitate easy taping of the connector and helps insure a moisture-proof seal to the insulation. A recess at the cable entrance

permits the end of the cable insulation to be inserted into the connector and thereby shrouds and protects the cut end of the insulation. The illustration shows the terminal with the cap clamped on the conductor by means of hollow head cap screws. This type of connector, available in all cable sizes up to 3000 mcm, is also made with hexagon head cap screws set in recesses in the cap in such a manner that they can be tightened with an ordinary socket wrench.

Whiteprint Machine.—A new, medium-priced, model F whiteprint machine, introduced by the Ozalid Products Div., General Aniline & Film Corp., Johnson City, N. Y., consists of a printer and dry-developing unit built into a single, compact machine, combining all the facilities necessary to turn out

finished dry-developed Ozalid whiteprints. Equipped with a new type high pressure mercury vapor lamp, which uses 40 watts per inch and has an active length of 46 inches, the model F will print Ozalid sensitized materials at speeds up to 56 inches per minute. The lamp is guaranteed for 1,000 hours, but tests indicate a life of from 1,500 to 2,500 hours. Lamps which burn out can be reworked for considerably less than the purchase price of a new lamp. The efficiency of the new model F light source cuts current consumption more than 50 per cent of that required by other machines of similar capacity. Even cooling of the lamp, so necessary for uniform light distribution, is provided by a two-stage blower and a specially designed air duct. Maximum lamp efficiency is assured by a reactive type transformer equipped with condensers providing power factor correction to 87.5 per cent. A counter automatically registers the number of hours the machine operates.


"MEGGER"
TRADE MARK REGISTERED U.S. PAT. OFF.
Insulation Tester
More than a Fine Testing Instrument
. . . the symbol of a procedure among practical electrical men that anticipates insulation failure, forestalls trouble and saves lives and money.
Hand-Driven and Motor-Driven Sets in various ratings up to 10,000 megohms and 2500 volts d. c.
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1211-13 ARCH STREET · Electrical and Scientific Instruments PHILADELPHIA, PA.

Simplified Sound Measurements

With this Accurate, Highly Stable Meter

WITH THE IMPROVED General Radio Sound-Level Meter the intensity of sound can now be measured conveniently, quickly and accurately by anyone. This instrument is widely used throughout industry for all types of noise measurements and studies. It is completely self-contained and portable and will measure the intensity of sound from a whisper to a steam whistle.

FEATURES:

1 **EXCEPTIONALLY WIDE RANGE**—24 to 140 db

2 **SIMPLIFIED CONTROLS**—complete db range covered by a single control knob

3 **IMPROVED MICROPHONE**—special type of great sensitivity, highly rugged, unaffected by ordinary changes in temperature and humidity

4 **PLUG-IN MICROPHONE**—normally used directly on folding socket on instrument but can be detached and used with cable and tripod if desired

5 **SLOW-FAST METER**—two speeds—control switch selects either; "fast" position, meter movement corresponds to A. S. A. standards; "slow" position, meter heavily damped to measure average level fluctuations.

6 **INTERNAL CALIBRATION SYSTEM**—calibration can be checked quickly from built-in calibrator

7 **THREE WEIGHTING NETWORKS**—low level, high level and substantially flat overall response

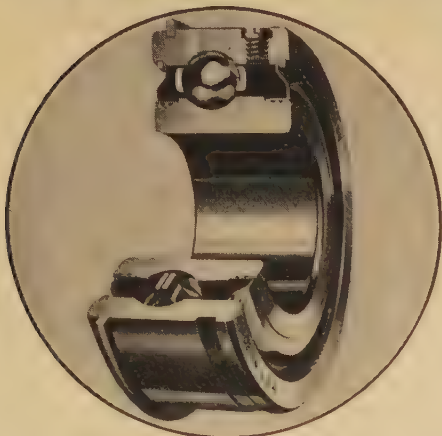
8 **NO COILS**—instrument contains no coils or inductances and accordingly reads accurately in the presence of any ordinary magnetic field

TYPE 759-B SOUND-LEVEL METER.......................... $195.00

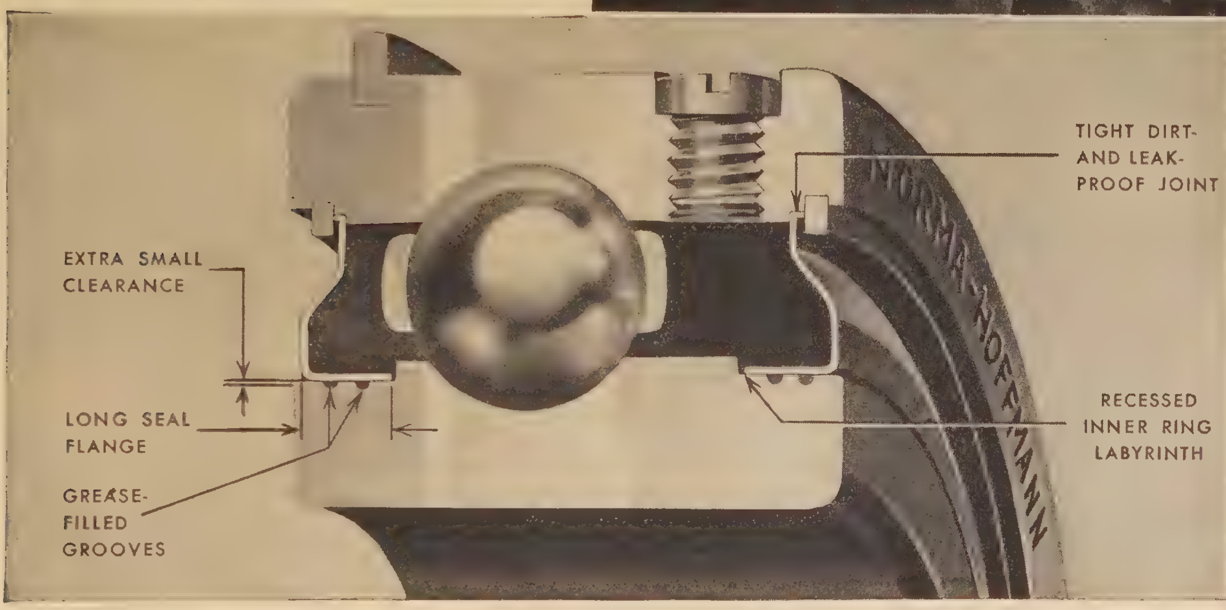
• **Write for Bulletin 659 for Information**

GENERAL RADIO COMPANY, Cambridge, Massachusetts

FULLY PROTECTED AGAINST DIRT



Made to Standard Double-Row Widths
WITH 100% GREATER GREASE CAPACITY



A clean, well-lubricated bearing is practically wearless. Dirt, however, will relentlessly destroy it. KEEP DIRT OUT AND KEEP THE GREASE IN, and you are protected against noise, rejections, and premature wear.

In the illustration herewith, note the five distinctive features that exclude dirt from the "CARTRIDGE" BALL BEARING. That minute clearance between the long seal flange and recessed inner ring is ALWAYS filled with grease. The grease grooves in the inner ring are so many added "dams" against the entrance of dirt.

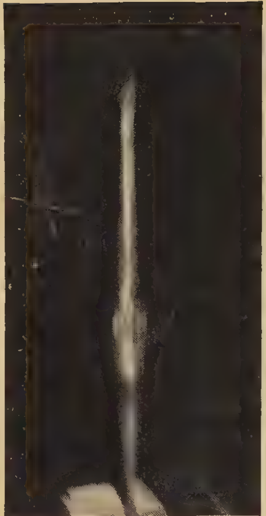
Thus, without any additional closures, the integral "CARTRIDGE" seals KEEP THE DIRT OUT AND THE GREASE IN—regardless of the position of motor or unit. In assembling or disassembling in the shop, the "CARTRIDGE" BALL BEARING STAYS CLEAN because its internal parts are never exposed.

Adopt the "CARTRIDGE" BALL BEARING as insurance against dirt and grease contamination, and against neglected lubrication. It eliminates numerous supplementary closure parts and machining operations and variables, and speeds up production; and it has convenient regreasing and inspection features.

Write for the Catalog. Let our engineers work with yours.

NORMA-HOFFMANN BEARINGS CORPORATION, STAMFORD, CONN., U. S. A.

Damage TO INSULATION
Slippage BETWEEN FOIL AND PAPER
Leakage DEVELOPED
None!



DROPPED! Unharmed after crashing on end to the floor six times from heights of 10 to 25 feet, this Westinghouse Condenser Bushing gives dramatic proof of rugged mechanical construction and lasting insulation qualities.

INTACT! Examination after six succeeding drops of 10 to 25 feet disclosed no damage. Standard commercial high potential and power factor insulation tests showed bushing electrically unaffected—air pressure test proved condenser intact and free from leakage.

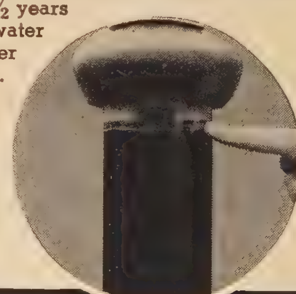
EXTREME TESTS PROVE STRENGTH OF MODERN WESTINGHOUSE CONDENSER BUSHINGS

The most compact in size, paper-wound condenser type bushings are the strongest as well. Constant improvement in materials and processes, together with drastic tests have produced in today's Westinghouse Condenser Bushing a unit which defies moisture, extremes of temperature, and mechanical and electrical stresses.

Use of electrolytic copper foil now gives even greater adhesion between layers composing the condenser unit. The improved insulating compound between condenser and porcelain is non-hardening and is heavier than water. At lowest operating temperatures, perfect cohesion prevents voids, and adhesion to condenser and porcelain prevents moisture from reaching the condenser. New standardized cap fór all bushings improves top seal, makes testing easier.

Investigate what these improvements mean in new low costs for bushing maintenance and replacement. See your Westinghouse representative or write Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa., Dept. 7-N.

OVERVOLTAGE . . . UNDER WATER . . . 2½ YEARS! One of several Westinghouse Condenser Bushings tested continuously for more than 2½ years at 50% overvoltage with water on top of the plastic filler throughout the entire period. Absolutely no emulsification or moisture absorption has occurred. Power factor tests show no effect on electrical characteristics of the condenser insulation.



W WESTINGHOUSE ELECTRIC

Westinghouse
CONDENSER BUSHINGS

"Let's make sure we are using the *Right Steel!*"

THAT'S typical of plant managers who have learned to take advantage of the services of the Carnegie-Illinois electrical sheet specialists. These men are trained to know which sheet will give the best performance, the right electrical properties—to specify the proper grade and most economical sheet size to use. They are familiar with such problems as annealing and core plating. On the job day and night, they will stay with you until your trouble is licked. And because of their broad experience with the production of electrical equipment they are often able to help you in other ways.

Why not call in the man from Carnegie-Illinois? Problems arising from the use of electrical sheets should be his worry, not yours. Let him work your problem out right in your own plant. It won't cost a cent, and may save you a lot of money and production grief.

Make sure you have specified the right steel for *your* latest design.

U·S·S ELECTRICAL STEEL SHEETS

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UNITED STATES STEEL

Professional Engineering Directory

Employment Bulletin

Engineering Societies Personnel Service, Inc.

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the four offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

TRANSF ENGR, des, devpmt, sales or research, B.S.E.E., 1932; 29; can offer neatness, orderliness, ability and new ideas. E-736.

ELEC-MECH ENGR. Seven yrs large elec util cos gaining both const and oprtg exper, followed by 7 yrs leading consulting engg firms, thoroughly conversant with regulatory commission work. Desires pos, preferably at New York. E-737.

B.S.E.E., 1934; 29, married; exper meter dept, overhead distr; now employed as Managing Engr small util. Desires pos as distr engr or elec sales promotion engr. E-738.

B.S.E.E., Univ of Pa, 1934; Associate AIEE; 28, married; 5 yrs util exper, viz underground network, overhead transm and distr, step voltage regulators. Present rating, Engr, Distr. E-739.

B.S.E.E., 1938; Associate AIEE; 4 yrs com lab tech. 1 yr Field Intensity Research. Exper marine and broadcast radio oprtg. Instructor radio oprtg. Desires pos com. Available immed. E-740.

M.S.E.E., advanced work 2 excellent schs; N. Y. license; married; 10 yrs broad and intensive teaching, organizing and indus exper in pwr and com; desires opportunity in teaching, organizing, tech investigation. E-741.

SALES ENGR, 48, married; 25 yrs sales exper indus and constr elec. eqpt. Specialist ltg and pwr sales. Ability train, direct, build up sales. Seeking pos where develop. E-742.

ELEC ENGR, Fellow AIEE, professional license, varied util, indus exper, U. S. and abroad. Past 15 yrs chief engr, gen supt, util in Mississippi Valley; exper in continuing property records. E-743.

B.S.E.E.; 3 yrs Law, night, eligible Bar many states; 28, married; 6 yrs pub util com exper, rates, contracts, valuations, financial, depreciation and cost studies, oprtg problems, regulatory procedure. E-744.

ELEC ENGR, 18 yrs exper des, mfg, sales rotating elec machy. Chief engr several cos. Can handle engg mfg, application and sales. Seeks exec pos in elec or mech industry. E-745.

RECENT GRAD, elec and mech engr; 28, single; ambitious. Desires opportunity for exper leading to responsible engg pos. Interested in sales and production. E-746.

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ELEC GRAD, Pratt Inst, 1934, with some exper in air conditioning eqpt, install and maintenance. Desires pos in same, preferably in East. Available immed. E-748.

B.E.E.; 30, married; employed in meter dept, util co; 5 yrs exper util, steel mill, draftg office; util co or mfg pos desired; midwest preferred; Professional Elec Engr, Ohio. E-749.

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B.S.E.E., Col City of New York, recent grad; single. Desires pos with mfr of elec or mech prod. Location immaterial, salary secondary. Available immed. E-751.

M.S.E.E., Univ of Minn, 1938; 33, married; 18 mos exper pub util; asst to gen mgr; teaching exper; surveying exper; desires pos with engg future; now employed. E-752-261-Chicago.

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